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Co-digestion of livestock effluents, energy crops and agro-waste: Feeding and process optimization in mesophilic and thermophilic conditions

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HIGHLIGHTS

- ▶ The co-digestion of several substrates coming from agricultural sector was studied.
- ▶ We performed both batch and continuous trials under different operating conditions.
- ▶ The partial substitution of energy crops with agro-waste increases the biogas yields.
- ▶ The greatest biogas yields were reached in thermophilic conditions.

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ABSTRACT

In this study the optimization of the biogas yield from anaerobic co-digestion of manures and energy crops was carried out using four pilot scale CSTRs under different operating conditions. The effect on biogas yield of the partial substitution of energy crops with agro-waste was also investigated. For each substrate used during the continuous trials, BMP batch assays were also carried out to verify the maximum methane yield theoretically obtainable. Continuous operation results indicated that the co-digestion of manures, energy crops and agro-waste was viable at all operating conditions tested, with the greatest specific gas production of 0.54 $m^3/kg\ VS_{fed}$ at an organic load rate of 2 $kg\ TVS/m^3{}_r d$ consisting of 50% manure, 25% energy crops and 25% agro-waste on VS basis. No significant differences were observed between high and low loaded reactors suggesting the possibility of either improving the OLR in existing anaerobic reactors or reducing the design volumes of new reactors.

1. Introduction

Anaerobic digestion is one of the most common practices for the management of livestock manure because of the renewable biogas energy which can be obtained. A lot of biogas plants have been built as a consequence of European incentives for renewable energies (Lindorfer et al., 2008a; Bolzonella et al., 2011). Livestock effluents are characterized by a low carbon to nitrogen ratio (C/N) due to relatively high concentration of ammonia, limiting the biogas yields (Procházka et al., 2012). A way to decrease the risk of ammonia inhibition is the co-digestion of livestock effluents with energy crops. The addition of energy crops (mainly maize silage) with high carbon content balances the C/N ratio of the feedstock (Wang et al., 2012) increasing the energy balance of the reactors (Amon et al., 2007a) and optimizing the economic revenue derived from the European subsidies received (Bolzonella et al., 2011). However, energy crops need water, energy and fertilizers (Hanegraaf et al., 1998), decreasing, at the same time, the amount of arable land surface available for food crop production with a subsequent increase in the cost of food crops. Therefore, from a Life Cycle Assessment (LCA) point of view, these substrates are penalized (see Annex V.A in Directive 2009/28/EC on renewable energies). In addition, several environmental factors negatively influence their biodegradability (Amon et al., 2007b),

Abbreviations: AD, anaerobic digestion; AV, average value; COD, chemical oxygen demand; CSTRs, continuous stirred tank reactors; GPR, gas production rate; HRT, hydraulic retention time; *K*h, hydrolysis constant; NH_3, free ammonia; N-NH_4^+, total ammonia; OLR, organic load rate; P, phosphorus; PA, partial alkalinity; $R1_{H37}$, high loaded mesophilic reactor; $R2_{L37}$, low loaded mesophilic reactor; $R3_{L55}$, low loaded thermophilic reactor; $R4_{H55}$, high loaded thermophilic reactor; S.D, standard deviation; SGP, specific gas production; T, temperature; TA, total alkalinity; TKN, total Kjiendhal nitrogen; TS, total solids; TVS, total volatile solids; V, volume; VFA, volatile fatty acids; w.w, wet weight; d.w, dry weight.

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making energy crops an unfavorable feedstock. A cost effective way to facilitate future development of the agro-economy can be the substitution of energy crops with several kinds of agro-waste in AD plant feedstock (Schievano et al., 2009). Because of its abundance, agro-waste can be considered an ideal substrate to substitute energy crops in the co-digestion process. The anaerobic co-digestion of manure and agro-waste is already widely used in Europe (Weiland, 2010).

The performance in terms of biogas production and digestate quality depends on several parameters such us temperature, OLR, HRT and feedstock composition.

The effect of temperature on process efficiency has been investigated through different studies, although studies of both mesophilic and thermophilic digesters have conflicting results (Ward et al., 2008). Lindorfer et al. (2008b) showed that there is no general temperature optima in anaerobic digestion and process performance depends on many other parameters such as nitrogen load, hygienic requirements and plant design. Cavinato et al. (2010) showed that biogas production from the co-digestion of cattle manure and other organic waste can be increased when operating at proper thermophilic conditions (55 °C) and also a general improvement in digester behavior was clear considering the stability parameters. On the other hand, a decrease in thermophilic reactor performance may occur if free ammonia concentration exceeds approx. 0.7 g-N/l (Amon et al., 2007a,b; Angelidaky and Aharing, 1994; Cavinato et al., 2012).

As far as the organic load and retention time are concerned, in northern Italy most AD farm plants operate in the range of 1–3 kg TVS/$m^3{}_r$d with retention time always greater than 40 days (Bolzonella et al., 2011).

Several authors have showed that it is possible to increase the OLR of conventional biogas plants which treat both manure and energy crops but to avoid atmospheric emissions, the effluent storage of high loaded processes has to be integrated into the gas-tight system of the digesters (Lindorfer et al., 2008a; Comino et al., 2010; Menardo et al., 2011).

In the present paper we studied the optimization of anaerobic digestion of livestock effluents and co-treatment with energy crops under different operating conditions. The effect on biogas yields of the partial substitution of energy crops with agro-waste was also investigated. In particular four parallel pilot scale continuous stirred tank reactors were operated under different temperature conditions, organic load rate and hydraulic retention times.

2. Methods

2.1. Substrates and BMP assays

The substrates used for this experimentation, namely cattle slurry, cow manure, maize silage, triticale and agro-waste (potatoes and onions) came from an AD plant treating livestock effluents, energy crops and other organic co-substrates. Table 1 shows the average values found for the characterization of each substrate.

Cattle slurry and cow manure showed a TS content of 31% and 9% respectively, with a high volatile fraction (80% on TS). The COD/TS ratio was in the range of 0.83–0.92, indicating a high level of oxidation as expected for a "digested" substrate. Energy crops and agro-waste showed a higher VS concentration (more than 90%) with a COD/TS ratio greater than 1. As expected, livestock effluents showed a high nitrogen content: in the case of cattle slurry ammonia concentration was more than 50%, reaching concentrations as high as 2 g/L. Also, phosphorous showed concentrations in the range of 6–8 g/kg (as P).

On the other hand, energy crops and agro-waste showed lower concentrations of nutrients if compared with livestock effluents: in particular, energy crops showed N and P concentrations at around 13–17 g N/kg TS and 1.4–2.5 g P/kg TS respectively, while the concentrations of nutrients found for agro-waste were in the range of 23–27 g N/kg TS and 2–3 g P/kg TS, respectively.

For each substrate, BMP assays were performed both in mesophilic and thermophilic conditions for at least 30 days in accordance with the method described by Angelidaki et al. (2009). Each batch of assays was carried out in triplicate using 1 liter closed vessels, inoculated with 500 mL of digested sludge drawn from the farm-scale anaerobic digestion plant treating livestock effluents and other co-substrates. Before starting the assays, the sludge was maintained for 2 weeks at proper temperatures (37° and 55 °C) in order to acclimatize the microorganisms to the new thermal conditions.

2.2. Reactors and experimental design

Four parallel pilot scale CSTRs were used to study the combined influence of temperature, OLR, HRT and feedstock composition. Heating of the reactors was provided by an external heater and the reactor temperature control was carried out through resistance temperature detectors. The reactors were fed semi-continuously, 3 times per day. Table 2 shows the experimental operational conditions and feedstock composition used in the different runs adopted in this study.

The working volume of each reactor was 0.23 m^3. $R1_{(H37)}$ and $R2_{(L37)}$ and were maintained at 37 °C whereas $R3_{(L55)}$ and $R4_{(H55)}$ were operated at 55 °C. High (4 kg TVS/$m^3{}_r$d) and low (2 kg TVS/$m^3{}_r$d) organic loading rates were compared using two different hydraulic retention times, 30 days and 60 days for $R1_{(H37)}$/$R4_{(H55)}$ and $R2_{(L37)}$/$R3_{(L55)}$ respectively. In order to study the influence of feedstock composition, three runs were carried out (Table 2). RUN I was characterized by a feedstock consisting of cattle slurry and cow manure (livestock effluents) with a ratio 1.5:1 on a wet weight base, a typical situation for dairy farms. During RUN II, 50% of the OLR included the addition of energy crops (triticale and maize silage) and the remaining 50% consisted of livestock effluents on a VS basis, whereas during RUN III the OLR included 50% livestock effluents, 25% energy crops and 25% agro-waste respectively, on a VS basis. In order to control the TS concentration of feedstock, during RUN II and RUN III, part of the effluent liquid fraction of each reactor was recirculated in the influent feedstock mixing tank. The reactors were operated for 390 days in all.

Table 1
Average characteristics and standard deviation for the different substrates.

A.V ± S.D		TS (g/kg)	TVS/TS (%)	COD (g/kg TS)	TKN (g/kg TS)	P (g/kg TS)
LE	Cattle slurry	94 ± 45	79 ± 2	907 ± 245	38 ± 2	8 ± 2
	Cow manure	310 ± 35	80 ± 3	835 ± 201	49 ± 3	6 ± 0.5
ECs	Triticale	251 ± 51	90 ± 1	1050 ± 95	17 ± 1	1.4 ± 0.02
	Maize silage	347 ± 54	96 ± 1	1100 ± 112	13 ± 3	2.5 ± 0.02
AW	Onion	107 ± 15	93 ± 0.5	940 ± 85	27 ± 1	3 ± 0.02
	Potato	177 ± 28	94 ± 0.5	1000 ± 89	23 ± 1	2 ± 0.02