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Anaerobic co-digestion of solid waste: Effect of increasing organic loading rates and characterization of the solubilised organic matter

Rangaraj Ganesh [a], Michel Torrijos [a,*], Philippe Sousbie [a], Jean Philippe Steyer [a], Aurelien Lugardon [b], Jean Philippe Delgenes [a]

[a] *INRA, UR50, Laboratoire de Biotechnologie de l'Environnement, Avenue des Etangs, Narbonne F-11100, France*
[b] *Naskeo Environnment, 52 rue Paul Vaillant Couturier, F-92240 Malakoff, France*

HIGHLIGHTS

- ▶ Co-digestion of waste studied at a low OLR of <2 $kgVS/m^3$ d yielded 0.33 l CH_4/gVS fed.
- ▶ OLR increase to a maximum of 7.5 $kgVS/m^3$ d resulted in 20% decrease in methane yield.
- ▶ COD solubilised at high loading was characterized for biodegradability and size-fractionation.
- ▶ Biodegradability of the solubilised organic matter ranged between 10% and 38%.
- ▶ Solubilised COD comprised mostly (82%) of colloidal and very fine particulate organics.

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ABSTRACT

The impact of stepwise increase in OLR (up to 7.5 $kgVS/m^3$ d) on methane production, reactor performance and solubilised organic matter production in a high-loading reactor were investigated. A reference reactor operated at low OLR (<2.0 $kgVS/m^3$ d) was used solely to observe the methane potential of the feed substrate. Specific methane yield was 0.33 l CH_4/gVS at the lowest OLR and dropped by about 20% at the maximum OLR, while volumetric methane production increased from 0.35 to 1.38 m^3CH_4/m^3 d. At higher loadings, solids hydrolysis was affected, with consequent transfer of poorly-degraded organic material into the drain solids. Biodegradability and size-fractionation of the solubilised COD were characterized to evaluate the possibility of a second stage liquid reactor. Only 18% of the organics were truly soluble (<1 kD). The rest were in colloidal and very fine particulate form which originated from grass and cow manure and were non-biodegradable.

1. Introduction

Anaerobic co-digestion, where two or more types of waste are treated in the same digester, has aroused renewed interest due to its inherent advantages. Common benefits of co-digestion include easier handling of mixed waste (Li et al., 2009), adjustment of the carbon-to-nitrogen (C:N) ratio (Xie et al., 2011), dilution of potential toxic compounds, improved balance of nutrients, increased loads of biodegradable organic matter (Gannoun et al., 2007; Bouallagui et al., 2009) and increased gas yields (Fountoulakis et al., 2008; Macias-Corral et al., 2008). Thanks to the positive synergistic effects, the overall result was higher mass conversion and lower weight and volume of residual digested matter (Macias-Corral et al., 2008).

Large-scale biogas plants are often built merely on the basis of conventional plant design or even rule-of-thumb (Lindorfer et al., 2008; Appels et al., 2011) resulting in under or over design. Laboratory and pilot-scale testing on the optimum and maximum organic loading rate applied for the specific substrates involved in co-digestion is highly important for the design and upgrading of biogas plants. Such experiments make it also possible to gain details on system overloading (Angelidaki et al., 2004). Based on pilot-scale studies, Comino et al. (2010) have concluded that most agricultural biogas plants have potential for significant increase in capacity and technological improvements.

The optimization of the organic loading rate (OLR) and the influence of high-loading rates on the post-methane potential of reactor

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[*] Corresponding author. Tel.: +33 468425185; fax: +33 468425160.

E-mail addresses: sairganesh@yahoo.com (R. Ganesh), torrijos@supagro.inra.fr (M. Torrijos), sousbie@supagro.inra.fr (P. Sousbie), steyer@supagro.inra.fr (J.P. Steyer), aurelien.lugardon@naskeo.com (A. Lugardon), delgenes@supagro.inra.fr (J.P. Delgenes).

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digestate was a subject of research by several authors. Increase of OLR from 2.11 to 4.25 kgVS/m^3 d in an agricultural biogas plant fed with energy crops and manure resulted in almost double the volumetric biogas production. However, higher loading led to undegraded organic material in the digestate, which resulted in an increase in the residual methane potential by a factor of 10 (Lindorfer et al., 2008). OLR increase from 4.45 to 7.78 kgVS/m^3 d in a pilot biogas plant for the co-digestion of cow manure and crop silage mix was investigated by Comino et al., 2010. At higher OLR, volumetric methane production increased, but the retention times apparently became too short for efficient degradation. The post-methane potential of digestate from the co-digestion of energy crops, crop residues and cow manure, for loading rates between 2 and 4 kgVS/m^3 d, was 0.9–2.5 m^{3}CH$_4$/t wet weight of digestate corresponding to 12–31% of total methane production (Lehtomäki et al., 2007). At the OLR of 3 kgVS/m^3 d, post-methane production potentials of digestates ranged from 38% to 41% of total methane production potentials of the feedstock (Xie et al., 2012). The relatively short HRT and the high OLR in conventional CSTRs were cited as the main reasons for the high post-methane production potential. For few biogas plants in Germany, which were one stage CSTR systems, a residual methane potential of 10%, which reached up to 25% at 20 °C, was observed by Weiland et al. (2004). The post-methane potential if not recovered, gets lost as atmospheric emissions, which emphasizes the need for residual gas collection in covered storage tanks (Xie et al., 2012; Comino et al., 2010; Lindorfer et al., 2008; Lehtomäki et al., 2007; Angelidaki and Ahring, 2000). The storage of digestate from dairy cow manure digestion for a period of 6 months led to the production of an additional 30% methane production (Kaparaju and Rintala, 2003). The use of two CSTRs in series was suggested by Kaparaju et al. (2009) for the digestion of cow manure, whereby 13–17.8% more methane was obtained compared to a one-step process.

Review of literature showed that past research was mainly concerned with the estimation of post-methane potential of digestate from digesters operated under high-loading conditions, stressing the need for post-treatment facilities. However hydrolysis under high-loading operation for the formation of solubilised organic matter (VFA and SCOD) was a subject almost untouched in the past. These solubilised organics can be subsequently utilized in a second stage liquid reactor after a solid–liquid separation phase, provided the biodegradability of SCOD formed is high. The second stage reactor can result in significant methane production. Characterization of the solubilised organic matter is vital in understanding its biodegradability. Molecular size distribution by filtration technique for the characterization of liquid effluent was carried out by few authors. Characterization of landfill leachates of different ages by molecular size distribution and the biodegradability of the effluent after aerobic and anaerobic treatment from a landfill was conducted by Amaral et al., 2009. Leachate fractions of size less than 1 kDa; between 1 and 10 kDa; between 10 and 100 kDa; and greater than 100 kDa were found to be refractory. The effect of organic and hydraulic shock loads on the production of soluble microbial products in anaerobic digesters and its characterization by ultrafiltration technique was investigated by Aquino and Stuckey (2004). Results showed that majority of the compounds were in the low MW range, with 35% found in MWs greater than 1 kDa.

The purpose of the present work was twofold. The first objective was to study the influence of an increase in the organic loading rate (OLR) on methane productivity in a high-loading reactor and to compare it with a reference reactor operated at a low loading rate. The effect of increased loading on the reactor performance viz., solids elimination and solubilised organic matter production were studied. The second objective was to characterize the solubilised organic matter in the liquid effluent from the high-loading reactor. The liquid effluent was obtained by centrifugation (solid–liquid separation) of the digestate from the reactors. The biodegradability and size-fractionation of COD of the liquid effluent by micro- and ultra-filtration were studied to understand the reasons for the degree of biodegradability. This characterization study was included in this research as it could indicate how best to incorporate a second-stage liquid reactor for the utilization of the hydrolysis products obtained during the high-loading operation of the solid-phase reactor, thereby aiding in the possible enhancement of the overall methane yield.

2. Methods

2.1. Feed substrates

A mixture of three different substrates viz., grass, cow manure with straw (CM) and fruit and vegetable waste (FVW) was used for the co-digestion study. Grass and CM were crushed to a size of approximately 1 cm in a Blik BB 230 crusher equipped with stainless steel rotating blades and then stored at −20 °C. For the preparation of FVW feed, equal quantities of apple, banana, carrot, potato and lettuce were ground to approximately 1 cm in size in the crusher and mixed thoroughly. For the whole experiment, five different batches of grass and one batch of CM and FVW were used for reactor feed. The composition of the three substrates and the proportion of weight used in the feed mixture are presented in Table 1. The pre-weighed and stored mixture of the three feed substrates was brought to room temperature and fed into the reactors. The calculated average total and volatile solids of the feed mixture were 22.8 ± 1.9% and 19.5 ± 1.6%, respectively.

2.2. Reactor set-up and operation

Three reactors were used in this study. The first reactor, called the reference reactor, was run at a low OLR throughout the experiment. In the second reactor, called the high-loading reactor, the OLR was increased step-wise. The third reactor, the biodegradability reactor, was run in series with the high-loading reactor and was fed with the supernatant obtained after centrifugation of the digestate from the high-loading reactor.

Two similar reactors were used, as shown in Fig. 1, for the reference and high-loading reactors. Experiments were carried out in double-walled stainless steel reactors maintained at 35 °C by a regulated water bath. The total volume of the reactors was 15 l with an effective sludge weight of 10 kg. Feeding and draining were carried out through an opening cover in the top part of the reactors. The reactors were equipped with a paddle-shaped stirrer powered by a 1 HP motor. Mixing times were programmed through a process controller. For the experiments, mixing time was fixed at 5 min/h. The reference and high-loading reactors were inoculated with 10 kg of anaerobic sludge obtained from a 1.2 m^3 anaerobic pilot plant treating distillery vinasse. The inoculum sludge had the following solids characteristics: TS = 7.2%, VS = 5.2%, VS/TS = 72.3%. Each reactor was placed on a weighing scale and the weight of the complete reactor set-up before and after the addition of the inoculum sludge was recorded. During reactor operations, the total weight of the reactor set-up was measured once a week and sludge withdrawal was accordingly adjusted to maintain the weight of the reactor sludge constant at 10 kg. Biogas produced passed through a moisture trap and then to a milligas counter fitted with a 4–20 mA output (MGC-1 gas flow meters, Ritter) and the data was recorded and displayed online. Software (Modular SPC) developed at the INRA laboratory was used to log the data.

For the biodegradability reactor, a double-walled glass reactor of 6 l volume maintained in mesophilic conditions at 35 °C was