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# A comparative study between single- and two-stage anaerobic digestion processes: Effects of organic loading rate and hydraulic retention time

Solmaz Aslanzadeh*, Karthik Rajendran, Mohammad J. Taherzadeh

*Swedish Center for Resource Recovery, University of Borås, Borås, Sweden*

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ABSTRACT

The effect of an organic loading rate (OLR) and a hydraulic retention time (HRT) was evaluated by comparing the single-stage and two-stage anaerobic digestion processes. Wastes from the food processing industry (FPW) and the organic fraction of the municipal solid waste (OFMSW) were used as substrates. The OLR was increased at each step from 2 gVS/l/d to 14 gVS/l/d, and the HRT was decreased from 10 days to 3 days. The highest theoretical methane yield achieved in the single-stage process was about 84% for the FPW during an OLR of 3 gVS/l/d at a HRT of 7 days and 67% for the OFMSW at an OLR of 2 gVS/l/d and a HRT of 10 days. The single-stage process could not handle a further increase in the OLR and a decrease in the HRT; thus, the process was stopped. A more stable operation was observed at higher OLRs and lower HRTs in the two-stage system. The OLR could be increased to 8 gVS/l/d for the FPW and to 12 gVS/l/d for the OFMSW, operating at a HRT of 3 days. The results show a conclusion of 26% and 65% less reactor volume for the two-stage process compared to the single-stage process for the FPW and the OFMSW, respectively.

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## 1. Introduction

The global energy demand is currently being met by coal and oil, which is depleting our resources, not to mention adding to the rise in the environmental problems as a result of the use of the fossil fuels. It is estimated that the energy demand will increase by a factor of two to three during this century (Weiland, 2010). Biogas from the wastes could be a part of the solution in the growing need for energy supply. According to Forgács (2012), about 10,000 biogas plants are currently operating in Europe, and the number of the plants is expected to increase by a factor of five within 10 years.

The methane production process from organic wastes such as the organic fraction from the municipal solid waste (OFMSW) and the industrial waste is today carried out by a sequence of biochemical transformations. The process can be separated into two steps: first, where hydrolysis, acidification, and liquefaction occur and second, where acetate, hydrogen, and carbon dioxide are converted into methane. All these reactions occur simultaneously in a single reactor (Forster-Carneiro et al., 2008). A balanced anaerobic digestion process demands that the rates of degradation be equivalent in size, in both phases (Angelidaki et al., 1999). Numerous studies have shown to improve the efficiency of single-stage reactors (Cecchi et al., 1991; Heo et al., 2004; Climenhaga and Banks, 2008; Forster-Carneiro et al., 2008). High methane yields have already been achieved during the digestion of total solids content less than 5% (Verrier et al., 1987; Cho et al., 1995; Heo et al., 2004; Zhang et al., 2007). However, in the single-stage processes, the organic loading rate (OLR) still remains unsatisfactory, at 1–4 kgVS/m$^3$/day (Verrier et al., 1987; Cho et al., 1995; Heo et al., 2004; Zhang et al., 2007). The most important reason for this limitation is that higher OLRs cause inhibition because of the accumulated volatile fatty acids (VFAs) (Ahring et al., 1995). In addition, at high OLRs, the retention times (HRTs) should be sufficient for the microorganisms to have enough time to degrade the substrate. Thus, there is a balance between the OLR and the HRT that must be determined in order to optimize the digestion efficiency and the reactor volume (Demirer and Chen, 2005).

The development of the high rate reactors was based on the immobilization of the biomass in the wastewater treatment systems, which improved the degradation rate of the anaerobic treatment systems by decreasing the retention time. However, a drawback of these systems is that they are usually suitable for dilute wastewater streams, which contain around 3% total

* Corresponding author. Tel.: +46 33 435 4620; fax: +46 33 435 4008.
*E-mail address:* Solmaz.Aslanzadeh@hb.se (S. Aslanzadeh).

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suspended solids with a particle size less than 0.75 mm (Revitt et al., 2010). This means that substrates with a high solid content should be solubilized before they can be introduced to these high rate systems. Therefore, a two-phase system is required in order to achieve a rapid digestion and more stable operation and a higher organic loading capacity. However, there are very little investigations on the application of substrates with a high total solid content in the two-stage processes.

Our earlier studies on evaluating the two-stage process, based on the pretreated and untreated waste textiles (Jeihanipour et al., 2013) as well as cotton and starch (Aslanzadeh et al., 2013) showed that the two-stage process can be beneficial using rather unconventional substrates. These studies indicate that the structure and the degradability of the material is one of the factors deciding the OLR and the HRT.

In this work, the effects of the OLR and HRT in the conventional one-stage and two-stage systems using the organic fraction of the municipal waste (OFMSW) and the food processing waste (FPW) with a high total solid content were compared. These two substrates are among the most common waste streams that are currently used for biogas production, which principally relies on single-stage systems.

## 2. Materials and methods

### 2.1. Substrates and inoculums

The substrates used in this study include the organic fraction of the municipal solid waste (OFMSW) and wastes from the food processing industry (FPW). The inoculum used in the continuous stirred tank reactor (CSTR) was obtained from a 3000-$m^3$ biogas plant (Borås Energy & Miljö AB, Borås, Sweden), treating municipal solid waste at thermophilic (55 °C) conditions. The UASB reactors were seeded using the granulated anaerobic sludge, which was provided from a pilot plant using an upflow anaerobic sludge blanket (UASB) reactor treating the municipal wastewater at Hammarby Sjöstad (Stockholm, Sweden). The FPW was obtained from the storage tank with a retention time of 3–4 days, before it was fed to the digester.

### 2.2. Experimental set up

#### 2.2.1. Reactors

The reactors, both CSTR and UASB, were built in-house from thermoplastic material polymethylmethacrylate (PMMA). The CSTR had a working volume of 3 l with an inner diameter of 18.5 cm and a height of 18.5 cm, whereas the working volume of the UASB was 2.25 l, with an internal diameter of 6.4 cm and a height of 70 cm. The temperature of the reactors were kept constant at 55 °C for the CSTR and 34 °C for the UASB using a thermal water bath allowing for water re-circulation through the reactor's water jacket during the entire digestion process. The reactors were equipped with a feed inlet, a liquid sampling point, an effluent outlet, and a gas line connected to the gas measuring system containing a gas sampling port. The CSTR was equipped with an impeller for continuous mixing. The inlet from the bottom of the UASB reactor was equipped with a mesh to stop the large particles from entering the reactor.

#### 2.2.2. Reactor seeding and start up

The CSTR inoculums were incubated at 55 °C for three days in order to stabilize it before use. The CSTRs were filled with 3 l of inoculums at the beginning of the experiment. The UASB reactors were inoculated with 1.3 l of granular anaerobic sludge, and the remaining volume of the reactors were filled with water.

#### 2.2.3. Reactors configuration

In the single-phase digestion, a CSTR was employed. The two-stage continuous process, on the other hand, consisted of a CSTR connected to a UASB reactor. The liquid of the CSTR was pumped continuously to the bottom of the UASB, and the effluent of the UASB reactor was continuously re-circulated back to the CSTR. In order to separate the particulate matter from the CSTR effluent, the outlet of the CSTR was connected to a sedimentation tank consisting of a 100 ml glass bottle, to separate and settle the large particles before pumping the liquid to the UASB. The reactor configurations are illustrated in Fig. 1. Both systems were fed once a day.

### 2.3. Experimental procedure

The semi-continuous digestions were carried out by feeding the bioreactors during the start up period by increasing the OLR by 0.5gVS/l/d until reaching the desired OLR (2 gVS/l/d). The HRT of the UASB in the two-phase process was controlled by adjusting the speed of the pump prior to each step. To achieve a steady state condition, each OLR was sustained for more than three HRTs in the CSTR. There were no solids withdrawn from the reactors except for the samples withdrawn for analyses during the entire experimental setup. The volume of the biogas produced was recorded continuously by the Automatic Methane Potential Testing System (AMPTS, Bioprocess Control AB, Sweden), and the composition of the gas was measured by gas chromatography. The liquid and gas sampling were performed 3 times a week during the start of the process. At higher OLRs and lower HRTs, however, the sampling was performed every day. The liquid samples were kept at −20 °C until the analyses were performed.

### 2.4. Analytical method

The total solid (TS) and the volatile solid (VS) content of the substrates were determined by drying the samples to a constant weight at 105 °C and 575 °C, respectively (Sluiter et al., 2005). The characterization of the substrate (Table 1) was carried out by Analys & Konsulat labouratoreiet (AK labbet, Borås, Sweden). The Kjeldahl nitrogen and protein contents of the substrates were determined according to the Swedish standard method ss-en 25663/NMKL 6-4 (Swedish Standard Institute, 1984). The ammonium concentration was measured according to the SIS 028134-1 method (Swedish Standard Institute, 1976), and the fat content was determined by the NMKL method 131 (Nordic Commity on Food Analysis, 1989).

The biogas production was measured using AMPTS, based on the water displacement. It was equipped with a computer to record the volume of the biogas produced from each reactor. The composition of the biogas produced was determined by a gas chromatograph (Auto System Perkin Elmer, Waltham, MA), equipped with a packed column (Perkin Elmer, 6′ × 1.8″OD, 80/100 Mesh). The gas chromatograph was equipped with a thermal conductivity detector (Perkin Elmer) at an inject temperature of 150 °C, detection temperature of 200 °C, and oven temperature of 75 °C. The carrier gas used was nitrogen, operated at a pressure of 0.70 bar and a flow rate of 40 ml/min at 60 °C. A pressure tight gas syringe with a volume of 250 μl (VICI, Precision Sampling Inc., LA) was used for the gas sampling. Liquid samples were analyzed for pH, alkalinity, TS, VS, COD (soluble chemical oxygen demand), and VFA.

Prior to the analysis of the alkalinity, COD, VFA, the samples were centrifuged at 17,000 rpm for 10 min and filtered through a 0.2-μm filter to remove any solid particles. The COD and the ammonium concentration was measured using a HACH apparatus equipped with a UV–Vis Spectrophotometer (HACH, Germany), using the digestion solution COD and ammonium vials at an

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