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Single-phase and two-phase anaerobic digestion of fruit and vegetable waste: Comparison of start-up, reactor stability and process performance

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ABSTRACT

Single-phase and two-phase digestion of fruit and vegetable waste were studied to compare reactor start-up, reactor stability and performance (methane yield, volatile solids reduction and energy yield). The single-phase reactor (SPR) was a conventional reactor operated at a low loading rate (maximum of 3.5 kg VS/m^3 d), while the two-phase system consisted of an acidification reactor (TPAR) and a methanogenic reactor (TPMR). The TPAR was inoculated with methanogenic sludge similar to the SPR, but was operated with step-wise increase in the loading rate and with total recirculation of reactor solids to convert it into acidification sludge. Before each feeding, part of the sludge from TPAR was centrifuged, the centrifuge liquid (solubilized products) was fed to the TPMR and centrifuged solids were recycled back to the reactor. Single-phase digestion produced a methane yield of 0.45 m^3 CH_4/kg VS fed and VS removal of 83%. The TPAR shifted to acidification mode at an OLR of 10.0 kg VS/m^3 d and then achieved stable performance at 7.0 kg VS/m^3 d and pH 5.5–6.2, with very high substrate solubilization rate and a methane yield of 0.30 m^3 CH_4/kg COD fed. The two-phase process was capable of high VS reduction, but material and energy balance showed that the single-phase process was superior in terms of volumetric methane production and energy yield by 33%. The lower energy yield of the two-phase system was due to the loss of energy during hydrolysis in the TPAR and the deficit in methane production in the TPMR attributed to COD loss due to biomass synthesis and adsorption of hard COD onto the flocs. These results including the complicated operational procedure of the two-phase process and the economic factors suggested that the single-phase process could be the preferred system for FVW.

1. Introduction

High-rate anaerobic reactors for wastewater treatment have been in use for quite some time yet there is a need for further research into reactor design and new avenues for the treatment of solid wastes. Given the growing demand for energy recovery and efficient disposal of solid waste, such research is vital.

Single-phase anaerobic systems, in which all three reactions of hydrolysis, acetogenesis and methanogenesis take place simultaneously in a single reactor have been the preferred reactor design for the majority of waste (Lissens et al., 2001; Bouallagui et al., 2005). However, the operation of such systems at a high OLR and for waste with large biodegradable organic content such as fruit and vegetable waste (FVW) becomes difficult as this type of waste undergoes rapid acidification resulting in the inhibition of methanogenic activity (Mata-Alvarez et al., 1992; Callaghan et al., 2002; Bouallagui et al., 2009). The maximum loading rate reported for single-phase digestion of FVW was within 3.6 kg VS/m^3 d (Verrier et al., 1987; Mata-Alvarez et al., 1992; Bouallagui et al., 2003; Lin et al., 2011). Two-phase systems, in contrast, have the advantage of buffering the OLR in the first stage, allowing a more constant feeding rate to the methanogenic second stage (Bouallagui et al., 2005; Koutrouli et al., 2009; Ghosh et al., 2000). Higher loading rates in the range 5.7–7.7 kg VS/m^3 d were reported for the two-phase digestion of FVW (Verrier et al., 1987; Mtz.-Viturtia et al., 1995; Dinsdale et al., 2000; Rajeshwari et al., 2001; Bouallagui et al., 2004). The different types of oxido-reductive activities, pH optima and growth rates of acidogens and methanogens have been capitalized by phase separation to increase process efficiency

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(Mata-Alvarez, 1987; Shin et al., 2001; Parawira et al., 2008; Salomoni et al., 2011). In two-phase systems, simultaneous liquefaction along with acidification helps in handling waste with high solid content (Salomoni et al., 2011). For easily fermentable waste, the overall retention time in a two-phase reactor can be lower than that in a single-phase reactor (Gunaseelan, 1997). However, the process can often be slow, primarily because of the long start-up period (Hai-Lou et al., 2002).

Different configurations and combinations of acidification and methanogenic reactors for two-phase anaerobic systems have been used by several authors for treating FVW and allied wastes. Some of the systems studied for FVW have been CSTR – upflow filter bed (Zhu et al., 2009), coupled anaerobic SBRs (Bouallagui et al., 2004), tubular reactor (Bouallagui et al., 2003), solid bed hydrolyser – UASB methaniser (Rajeshwari et al., 2001), hydrolyser with raschig rings – inclined tubular digester (Dinsdale et al., 2000), ASBR hydrolyser – anaerobic filter methaniser (Raynal et al., 1998) and CSTR hydrolyser – anaerobic filter methaniser (Verrier et al., 1987), CSTR reactors for municipal solid waste (MSW) (De Gioannis et al., 2008); cascade process for organic waste (Chen et al., 2007) and hybrid anaerobic solid–liquid bioreactor for food waste (Hai-Lou et al., 2002; Stabnikova et al., 2008). These processes differed mainly in the way microorganisms were retained in the bioreactor and in the phase separation of acidogenic process from the methanogenic process (Bouallagui et al., 2005).

In the present investigation, a two-phase system was used in which the first-stage acidification reactor worked on the principle of decoupling the solids retention time (SRT) and the hydraulic retention time (HRT). Solid–liquid separation of digestate by centrifugation was followed by 100% recirculation of solids back to the reactor and the liquid extracted was fed to the methanogenic reactor for methane production. Solids recirculation was intended to increase the SRT and enhance microbial activity and thereby enhance the degradation of organic matter, while methanogenic effluent recirculation was to provide alkalinity and to maintain a constant solids concentration in the reactor and also for possible enhancement of solids hydrolysis. The uniqueness of this system was the solid–liquid separation technique by centrifugation compared to the mostly adopted method of leachate removal by percolation. Centrifugation was included to aid in efficient solid–liquid separation and better recirculation control. Recirculation techniques have been adopted by many authors for food waste and MSW (Hai-Lou et al., 2002; Chen et al., 2007; Bhattacharyya et al., 2008). The concept of recirculation was apparently introduced from landfill management where the recirculation of landfill leachate was found to enhance microbial activity and waste stabilization (Reinhart and Al-Yousfi, 1996; Stabnikova et al., 2008). Recirculation of leachate and methanogenic effluent to the acidification reactor was found to improve pH buffering (Chugh et al., 1998; Gomec and Speece, 2003).

The purpose of the present work was to assess the start-up, reactor stability and process performance of the two-phase anaerobic system and to compare it with a conventional single-phase system using fruit and vegetable waste as the feed substrate. Start-up of the acidification reactor of the two-phase system by evaluating the appropriate loading rate at which the methanogenic inoculum sludge could be converted to acidifying sludge, followed by operating in acidification condition was part of the objective. Application of a high loading rate coupled with recirculation of digestate after centrifugation was expected to meet the objective of acidification. Bibliographic survey showed that there are studies which have dealt with the single-phase or two-phase digestion of FVW and other organic solid waste (Shen et al., 2013), but comparison study of the two-processes using the same waste are scarce. In this study, the two processes were also compared by assessing the material and energetic balances.

2. Materials and methods

2.1. Feed substrates

Fruit and vegetable waste (FVW) was used as the feed substrate for the experiments. For the preparation of FVW feed, equal quantities of apple, banana, carrot, potato and lettuce (Bouallagui et al., 2004) were reduced to approximately 1 cm size in a Blik BB 230 crusher equipped with stainless steel rotating blades, mixed thoroughly and then stored at −20 °C. The composition of FVW is presented in Table 1. Pre-weighed and stored batches of the feed substrate were brought to room temperature and then fed into the reactors. The average total solids (TS) and volatile solids (VS) of the feed mixture were 12.7 ± 0.9% and 11.0 ± 0.8% respectively.

2.2. Reactor set-up

Three reactors were used in this study. The first reactor was a single-phase reactor (SPR) and was run in conventional mode. The two-phase system was made up of two reactors: the two-phase acidification reactor (TPAR) and the two-phase methanogenic reactor (TPMR). Two identical reactors as shown in Fig. 1(a) were used as the SPR and TPAR. They were double-walled reactors made of stainless steel and 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 manually by opening the top cover of the reactors. The reactors were equipped with paddle-shaped stirrers powered by a 1 HP motor and the mixing times were programmed through a process controller. For the TPMR, a double-walled glass reactor of 6 l volume was used and was maintained in mesophilic conditions at 35 °C. Biogas produced in the reactors passed through a moisture trap and then to a milligas counter fitted with a 4–20 mA output (MGC-1 gas flow meters, Ritter); the data was recorded and displayed online. Software (Modular SPC) developed at the INRA laboratory was used to log this data.

The SPR and TPAR were placed on weighing scales and the weight of the reactor before the addition of inoculum was measured and noted down. During reactor operation, the total weight of the reactor was measured once a week using the weighing scales and digestate withdrawal was adjusted accordingly to maintain the weight of the digestate in the reactor constant at 10 kg. This procedure was followed to minimize the error in solids destruction calculations. Since the weight depends on the concentration of the sludge, the specific gravity of sludge was used to make the corrections for the working volume. For the range of TS concentration (2.4–3.5%) in the SPR, specific gravity of the sludge varied between 1.002 and 1.003. And for the TPAR, TS varied over a wide range between 3.5% and 10.3% and specific gravity of the sludge varied between 1.003 and 1.020. From the specific gravity of the sludge, the working volume of the reactor was calculated and OLR corrected accordingly.

Table 1
Composition of fruit and vegetable waste (FVW).

Parameters	Value
TS (%)	12.7 ± 0.9
VS (%)	11.0 ± 0.8
VS/TS (%)	86.8 ± 3.7
COD (g/g)	0.136
COD/VS (g/g)	1.16
Soluble fraction (%)	75.9
Cellulose fraction (%)	3.9
Hemi cellulose fraction (%)	19.2
Lignin fraction (%)	1.0