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Anaerobic co-digestion of vegetable waste and swine wastewater in high-rate horizontal reactors with fixed bed

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ABSTRACT

Considering the high waste generation that comes from agriculture and livestock farming, as well as the demand for natural gas, it is necessary to develop sustainable technologies which can reduce environmental impact. There is no available literature on the use of high-rate horizontal anaerobic reactors with fixed bed (HARFB) and continuous feed for the co-digestion of vegetable wastes (VW) and swine wastewater (SW). The aim of this work was to evaluate the reactor performance in terms of methane production, organic matter consumption, and removal of total and thermotolerant coliforms under different proportions of SW and VW, and organic loading rates (OLR) of 4.0, 5.2 and 11.0 g COD $(\mathrm{L\ d})^{-1}$. The mixture of SW and VW in the proportions of 90:10, 80:20 and 70:30 (SW:VW) with those OLRs provided great buffering capacity, with partial alkalinity reaching 3552 mg L^{-1} thereby avoiding the inhibition of methane production by volatile fatty acids produced during the fermentation process. Higher proportions of VW and higher OLR improved volumetric methane production with a maximum value of 1.08 L CH_4 $(\mathrm{L\ d})^{-1}$, organic matter removal rates up to 98% and total and thermotolerant coliform removal rates of 99% were also observed.

1. Introduction

Increasing worldwide demand for food and food by-products stems from the increase in human population and has resulted in the generation of large quantities of solid organic waste. Approximately 37% of the animal protein consumed worldwide comes from pig farming (McGlone, 2013). The intensification of livestock systems in feedlots result in the production of high volumes of wastewater from a small area (Abouelenien et al., 2014).

In the agricultural sector, approximately 1.5 billion ton/year of fruit and vegetable were produced worldwide and 45% of them were wasted. In Latin America, losses reach 55% (FAO, 2011). In Brazil, approximately 60% of banana and up to 86% of tomato produced have been lost in the postharvest (Lichtemberg et al., 2008; Henz and Moretti, 2005). As a consequence of the build-up of solid organic waste in sanitary landfills, percolated liquids and greenhouse gases are produced because of the elevated concentrations of organic matter and humidity that come from this type of waste (Lin et al., 2011). These impacts can be reduced through the exploration of renewable energy sources (Di Maria et al., 2015) and improvement or development of easy-to-implement locally adaptable solutions especially in developing countries (Duda et al., 2015).

Due to increased demand and rising prices for fossil fuels, vegetable biomass has already been converted into renewable energy as a sustainable alternative. In Europe nowadays, biomass contributes 4% of the total energy supply. According to the European Commission Renewable Energy Directive, the use of renewable energy should contribute 20% by 2020 (Gissén et al., 2014).

Biogas production is one of several tools that may be used to alleviate the problems of global warming, energy security and waste management. Anaerobic digestion is an efficient alternative technology for the treatment of wastewater, agricultural waste, food processing waste, and fruit and vegetable debris as well as for sludge stabilization. Its advantages are the production of renewable fuel as biogas, the agricultural recycling of organic matter and the recovery of remaining nutrients in the effluents of the anaerobic reactors (Appels et al., 2011).

However, the solid waste from fruit and vegetables degrades quickly, which makes the acidification process easier, causing the accumulation of volatile fatty acids and consequently decreasing

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pH, inhibiting the activity of methanogenic archaea (Bouallagui et al., 2009). The excess ammonia can also inhibit the microbial consortia responsible for methane production (Nielsen and Angelidaki, 2008). Consequently, the anaerobic digestion of vegetable biomass is used with low OLR, at most 3 g VS $(L\,d)^{-1}$ without chemical supplementation (Jiang et al., 2012). The OLR can be increased by co-digestion with other biodegradable substrate (Bolzonella et al., 2006). The increase of OLR of 2.4–6.0 g VS $(L\,d)^{-1}$ in a food and fruit-vegetable wastes co-digestion with dewatered sewage sludge in anaerobic digester (CSTR) led to an increase of over 100% in methane production, of 0.97–2.40 L $(L\,d)^{-1}$, maintaining the percentage of methane between 56 and 57% (Liu et al., 2012). With a higher OLR, of 7.5 g VS $(L\,d)^{-1}$, the co-digestion of grass, cow manure and fruit-vegetable wastes in CSTR reached maximum methane production of 0.94 L $(L\,d)^{-1}$ (Ganesh et al., 2013). Thus, besides of OLR the type of waste used in the anaerobic co-digestion can affect methane production.

In order to enhance biogas production, the improvement of reactor design has a strong effect on anaerobic digestion performance (Namsree et al., 2012). Developed for the anaerobic treatment of liquid effluents, high-rate anaerobic reactors are characterized by their ability to retain large quantities of microbial biomass and allow for the use of low hydraulic detention time (HDT) and high OLR, which differs from conventional digesters. Particularly, horizontal anaerobic reactors with fixed bed (HARFB) a new generation of high-rate biological reactors, where it is possible to maintain high concentrations of biomass immobilized on the support, permit continuous horizontal outflows that approach plug-flow and HDT relatively short for high OLR (Zaiat et al., 1994; Ghaniyari-Benis et al., 2009). Besides, they provide advantages such as low area requirements and structural complexity facilitating their implementation in small and large scale (Oliveira and Bruno, 2013).

The HARFB have shown great efficiency for biogas production and organic matter removal from different agricultural and livestock effluents. The use of in-series HARFB for the treatment of SW and coffee fruit processing wastewater increased suspended solids, chemical oxygen demand (COD), metals, and coliform bacteria removals and methane production, while reducing HDT and improving system stability (Santos and Oliveira, 2011; Oliveira and Bruno, 2013; Duda et al., 2015).

However, there is no available information in the literature about the use of HARFB for the co-digestion of VW, because that has generally been conducted in batch and continuous complete-mix digesters with semi-solid and solid affluents. Therefore, the aim of this work was to evaluate methane production, removal of organic matter and coliforms in the anaerobic co-digestion process in HARFB using liquid affluents with high suspended solids concentrations, of 2–10 g L^{-1}. This is the first time that such reactors have been evaluated for the treatment of SW and VW in different co-digestion proportions.

2. Materials and methods

2.1. Substrate

The SW was collected three times a week from feedlot system during growing-finishing phase. This wastewater was sieved in 3 mm mesh.

The VW (banana and tomato) was collected in grocery stores, milled in industrial blender and then sieved in 2 mm mesh. The banana and tomato extract was stored in a freezer due to large volumes needed for the tests. VW consisted of 70% tomato and 30% banana extracts by wet volume.

The SW and a mixture of SW and VW constituted the substrates used as affluent for the reactors system and their characteristics are shown in Table 1.

2.2. Reactor configuration, start-up and operation

The experimental system consisted of an affluent storage reservoir and three in-series HARFB (R1, R2 and R3) at pilot scale (Fig. 1). The HARFB were built according to Zaiat et al. (1994). Characteristics of the experimental setup are detailed in Table 2. The HARFBs were built with 6 m PVC tubes with internal diameters of 0.108, 0.153 and 0.191 m to obtain relations $L/D > 25$ and consequently plug-flow reactors (Sauer et al., 2015).

The reactors system was arranged so that the speeds were decreasing from the first to the third reactor (Table 3). In order to enhance the conversion of soluble organic compounds in the first reactor, increase the time to hydrolysis, and decrease the drag of organic suspended solids in the second and third reactors. Thereby improve the production of methane and the quality of the final effluent.

To build the fixed bed for biomass immobilization, the reactors were totally filled with bamboo rings with specific surface area of 92.5 $m^2\,m^{-3}$, with average length and diameter of 0.046 m and 0.025 m, respectively. The bamboo rings with 75% empty space provided the support medium for fixed bed reactors R1–3. There was no clogging problem with the proportions SW:VW used.

At the top of each reactor were made six orifices for biogas exits. These were interconnected and coupled to a gasometer to store the biogas produced daily (Fig. 1). The reactors have registers along their length: seven on the sides to collect effluent samples, and six on the lower part to collect sludge.

The reactors were inoculated with anaerobic sludge from HARFB used by Duda et al. (2015) to treat SW. The inoculum sludge had concentrations of total solids (TS) 16 g L^{-1} and volatile solids (VS) 12 g L^{-1}. To start-up the inoculated amount was 30% of total volume for each reactor.

Four experimental tests (1–4) with durations of 65, 53, 46 and 37 days were run, totaling 201 days of reactors operation. The reactors system was operated at room temperature and the average air temperatures were 22 °C, 19 °C, 20 °C and 24 °C in the tests 1–4, respectively. The end of each test was reached when the biogas production was stable. The operational conditions of reactors system are show in Table 3.

The HDT and OLR were defined from experimental results obtained by Duda et al. (2015) in treatment system with HARFB. Using SW with COD of 5886 mg L^{-1} applied OLR 12–33 g COD $(L\,d)^{-1}$ and HDT 1 d obtained COD_{total} removal efficiencies below 80% and methane volumetric production around 1.0 L $(L\,d)^{-1}$. In view of the risk of acidification with VW mixture, for start-up in test 1 OLR around 5 g COD_{total} $(L\,d)^{-1}$ was adopted which resulted in 2 d HDT in R1. OLR of tests 2–4 were the result of the COD_{total} of mixture of increasing proportions of VW divided by HDT 2 d in R1.

Therefore, in the test 1, the affluent of reactors system was SW. In the test 2, the affluent was the mixture of SW and 10% of VW. In the tests 3 and 4, the mixture had volume of VW increased to 20% and 30%, respectively (Table 1).

The HDT in reactor system was 13 d in the four tests. In the first reactor, it was 2.0 d, second 4.5 d and third 6.5 d. Consequently, the OLR applied in the first (R1) reactor was obtained by the division between affluent COD_{total} of each test (Table 1) and HDT of 2.0 d. The characteristics of SW varied during the experiment and its COD_{total} decreased in the tests 2 and 3 because of the variations in age of the pigs and the amount of water used in feedlot system. Thus, the OLR in the tests 2 and 3 were lower. The OLR in second (R2) and third (R3) reactors varied depending on the values of