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Anaerobic digestion and co-digestion processes of vegetable and fruit residues: Process and microbial ecology

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ABSTRACT

This study evaluated the feasibility of methane production from fruit and vegetable waste (FVW) obtained from the central food distribution market in Mexico City using an anaerobic digestion (AD) process. Batch systems showed that pH control and nitrogen addition had significant effects on biogas production, methane yield, and volatile solids (VS) removal from the FVW (0.42 m^3_{biogas}/kg VS, 50%, and 80%, respectively). Co-digestion of the FVW with meat residues (MR) enhanced the process performance and was also evaluated in a 30 L AD system. When the system reached stable operation, its methane yield was 0.25 (m^3/kg TS), and the removal of the organic matter measured as the total chemical demand (tCOD) was 65%. The microbial population (general *Bacteria* and *Archaea*) in the 30 L system was also determined and characterized and was closely correlated with its potential function in the AD system.

1. Introduction

In recent years, concern has increased about waste disposal from mega cities, such as Mexico City, which has a population of more than 20 million people and produces a tremendous amount of solid waste, more than 12,000 tons per day. Large volumes of organic waste are disposed of in the Bordo Poniente sanitary landfill, the only landfill in the area, which is approaching capacity. Because no other locations exist for solid waste disposal, the application of efficient technologies for waste treatment and volume reduction is becoming increasingly important (Forster-Carneiro et al., 2008). Interest is also increasing in the production and use of alternative energy sources due to the limited supply of fossil fuels and their negative effects on the environment (Rittmann et al., 2008). The organic fraction of municipal solid wastes that is mechanically sorted in central plants (OFMSW) or the organics that are separated at the source, referred to as biowaste (the vegetable–fruit–garden or VFG fraction) could be a good candidate for bioenergy production. Fruit and vegetable waste (FVW) is produced in large quantities in markets in many large cities (Mata-Alvarez et al., 1992; Misi and Forster, 2002; Bouallagui et al., 2003, 2005) and constitute a nuisance in municipal landfills because of their high biodegradability (Misi and Forster, 2002). The central market for food distribution in Mexico City, Central de Abasto (CEDA), is the second largest market in the world, receiving 24,000 tons of food products and producing 895 tons of organic solid waste each day (Central de Abastos de la Ciudad de Mexico, 2011). Occasionally, food products in perfectly good condition are discarded because of the high cost of refrigeration storage. Approximately 84% of the total solid waste produced in CEDA is organic waste, and more than 50% of that is from the fruit and vegetable fraction (Silva-Rodriguez, 2007). The most promising alternative to incinerating or composting this waste material is to apply an anaerobic digestion process (Bouallagui et al., 2005) for simultaneous waste treatment and renewable energy production. The main advantage of the anaerobic digestion process is the production of biogas, which can be used to produce electricity. The stabilized biosolids can be used as a soil conditioner (Bouallagui et al., 2005). This technology has been successfully applied in reducing the volume of waste that enters landfills, thereby decreasing methane emissions produced by decay (Mata-Alvarez et al., 2000; Forster-Carneiro et al., 2008; Bouallagui et al., 2009).

Some authors have studied the feasibility of using FVW as a substrate for anaerobic digestion. The easily biodegradable and highly moist organic matter content of FVW (75%) facilitates the biological treatment of these wastes and demonstrates the feasibility of using this material for anaerobic digestion (Mata-Alvarez et al. 1992; Bouallagui et al., 2003, 2005, 2009). The

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FWV material is usually collected from food markets and has a volatile solid (VS) content of between 8% and 18% (Bouallagui et al., 2005). The organic fraction includes approximately 75% sugars and hemicellulose, 9% cellulose and 5% lignin (Verrier et al., 1987; Bouallagui et al., 2005). For most digestion processes, depending on the substrate used, hydrolysis is the rate limiting step (Vavilin et al., 1997; Mata-Alvarez et al., 2000). Hydrolysis constants were obtained from carbohydrates, protein and lipids, with the highest constant observed for carbohydrates, and these rates were determined to be pH-dependent (Mata-Alvarez et al., 2000). The anaerobic processing of cellulose-poor waste such as FVW is limited by methanogenesis rather than by hydrolysis (Bouallagui et al., 2005). The rate and extent of degradation are intrinsic properties of the waste characteristics and the microorganisms involved in the process. According to Mata-Alvarez et al. (1992), the FVW contains cellulose (32%), hemicelluloses (15%) and lignins (15%), and under mesophilic conditions, up to 32%, 86% and 0% of these compounds are removed, respectively. Gunaseelan (2004) reported the methane yields (B_0) of several fractions of FVW, sorghum and napiergrass. The methane potential depends on the organic components in the FVW used as feedstock, which are mainly carbohydrates, proteins and lipids. The theoretical methane yields (B_0) from acetic acid, carbohydrates, proteins and lipids are 370, 415, 496 and 1014 L CH_4/kg VS, respectively (Moller et al., 2004). B_0 could also be estimated considering that 1 kg of COD reduction is equivalent to 0.35 m^3 CH_4 (STP) (Gunaseelan, 2007).

The high biodegradability of the FVW promotes the rapid production of volatile fatty acids (VFAs) resulting in a rapid decrease in pH, which in turn could inhibit the methanogenic activity (Mata-Alvarez et al., 1992; Bouallagui et al., 2003, 2009). An interesting option to avoid the acidification of the system when FVW is used is the addition of co-substrates with high nitrogen contents, which could result in a natural pH regulation and also constitute a source of nitrogen. This strategy, known as co-digestion, results in a more efficient digestion process, improving the methane yields obtained from certain organic materials due to the positive synergistic effects of the mixed materials with complementary characteristics and the supply of missing nutrients by the co-substrate (Agdag and Sponza, 2005). Co-digestion also presents economic advantages, such as minimizing equipment needs by sharing the same equipment for different residues and easier handling of mixed waste (Mata-Alvarez et al., 2000). Habiba et al. (2009) studied co-digestion as a novel solution to adjust unbalanced nutrient constituents and reported that the anaerobic digestion of activated sludge (AS) with substrates containing high levels of C/N, such as FVW, overcame the difficulties of digesting AS. The addition of high nitrogen content co-substrates to adjust the nutrient content of FVW was recently evaluated by Bouallagui et al. (2009), and a methane yield of approximately 0.35 L/g VS was obtained without the addition of chemical alkali.

The aim of this study was to evaluate the potential use of FVW as a substrate for methane production and to examine various conditions that allow for anaerobic systems the optimal performance using FVW. A mixture of FVW from the biggest market in Mexico was characterized to assess its potential as a feedstock for an anaerobic digestion process. Additionally, the effects of: (1) pH, (2) nitrogen addition, and (3) inoculation of the FVW were evaluated to enhance methane production in batch systems. Co-digestion of the FVW with meat residues (MR) was also evaluated. The performance of a 30 L reactor was assessed under the most effective conditions obtained in the batch systems to determine the feasibility of converting the FVW and MR into biogas. The microbial ecology of the 30 L system when operating at steady state conditions was evaluated and its links to process performance were assessed using molecular methods.

2. Methods

2.1. Set up for the batch experiments

The biodegradability of the fruit and vegetable waste (FVW) was determined using batch anaerobic digestion tests. The characteristics of the FVW mixture are depicted in Table 1. FVW (50 g) with an initial total solid (TS) content of 98.9 g TS/$kg_{residues}$ (10% organic matter) was placed into 125 mL serum bottles that were sealed with butyl rubber septums and aluminum crimps and flushed with N_2 to provide anaerobic conditions. Some treatments were inoculated with 5 mL (10% v/v) of cow manure (density of the FWV was of 1.14 g/L). The FVW without inoculation or salt addition was used as a control, and the effects of inoculum (cow manure) addition, salts (to control the pH), and the addition of a nitrogen source were evaluated; the tested conditions are summarized in Table 2. For pH controlled systems, a 100 mM phosphate buffer with an initial pH of 7.0 was used. In the nitrogen supplemented systems, 0.08 g of NH_4Cl was used per g of waste, and the experiments were carried out with 50 g of FVW as mentioned above. All experiments were performed in duplicate. The systems were incubated at 30 °C for 30 days or until biogas production ceased. Each system was manually mixed once per day. Additionally, two control systems that only contained inoculum were incubated at the same temperature to correct for the amount of biogas produced by the organics in the inoculum. Statistical analysis was carried out with the NCSS statistical system (NCSS, PASS, and GESS, NCSS, Kaysville, UT, http://www.ncss.com).

2.2. Experimental setup (anaerobic digester)

The process was also evaluated in an anaerobic digestion system (ADS) consisting of a stainless steel tubular reactor with a total volume of 30 L into which 20 L of a (50:50) mixture of FVW

Table 1
Initial characteristics of the fruit and vegetable waste (FVW).

Solid waste	Organic matter (g/kg_{waste})	Total solids (g/kg_{waste})	Volatile solids (g/kg_{waste})	pH
Tomato	59.1	55.7	54.9	4.5
Lettuce	53.5	31.3	30.4	5.6
Papaya	85.5	116.5	114.4	5.5
Pineapple	72.7	102	99.2	3.5
Banana	107.6	181.2	176.4	5.0
Orange	115.5	153.2	149.4	3.8
Mixture of the solid waste	72.7	98.9	96.4	4.02

Table 2
Conditions established in eight systems (in duplicate) to evaluate the effects of inoculation, pH control and addition of a nitrogen source (0.08 g ammonium chloride/g_{waste}, with experiments conducted with 50 g of FVW) on the performance of the anaerobic digestion process.

System	Conditions
I	FVW inoculated with cow manure (10%)
IN	FVW inoculated and supplemented with NH_4Cl as a nitrogen source
IpH	FVW inoculated and salts added (buffer) to control pH
IpHN	FVW inoculated, buffering salts, and NH_4Cl added
wI	(VSW)
FVW	without inoculation (WI) (Control)
wIN	FVW and NH_4Cl
wIpH	FVW and buffering salts
wIpHN	FVW buffering salts and NH_4

I = inoculated systems, wI = systems without inoculum.