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Bio-energy conversion performance, biodegradability, and kinetic analysis of different fruit residues during discontinuous anaerobic digestion

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ABSTRACT

Huge amounts of fruit residues are produced and abandoned annually. The high moisture and organic contents of these residues makes them a big problem to the environment. Conversely, they are a potential resource to the world. Anaerobic digestion is a good way to utilize these organic wastes. In this study, the biomethane conversion performances of a large number of fruit residues were determined and compared using batch anaerobic digestion, a reliable and easily accessible method. The results showed that some fruit residues containing high contents of lipids and carbohydrates, such as loquat peels and rambutan seeds, were well fit for anaerobic digestion. Contrarily, residues with high lignin content were strongly recommended not to be used as a single substrate for methane production. Multiple linear regression model was adopted to simulate the correlation between the organic component of these fruit residues and their experimental methane yield, through which the experimental methane yield could probably be predicted for any other fruit residues. Four kinetic models were used to predict the batch anaerobic digestion process of different fruit residues. It was shown that the modified Gompertz and Cone models were better fit for the fruit residues compared to the first-order and Fitzhugh models. The first findings of this study could provide useful reference and guidance for future studies regarding the applications and potential utilization of fruit residues.

1. Introduction

The fierce and intense competition amongst different countries in terms of economic growth has led to a rapidly increasing energy consumption over the years. It was shown by the IEA's (International Energy Agency) most recent statistics that in 2012, the global primary energy consumption reached 13371 million tons of oil equivalents, increasing by 52.3% in the past two decades (IEA, 2015; Zhen et al., 2015). In China, more than 3 billion tons of standard coal equivalents were consumed for energy in 2009, however, non-fossil fuels only accounted for 9.9% (Jiang et al., 2011). China, as well as the world, is now facing a severe energy shortage crisis owing to the squander and overuse of fossil fuels. Therefore, developing new resources and fuels and taking full advantage of sustainable energy have become extremely important. One efficient and cost-effective alternative to fossil fuels is clean energy products produced through anaerobic digestion (AD).

AD, a technique that can convert different organic wastes to biogas (mainly composed of methane and carbon dioxide) at a relatively low cost, is receiving increasing attention. Numerous studies have been published on AD of different industrial, agricultural, and municipal organic wastes and residues (Ye et al., 2008; Cecchi and Cavinato, 2015; Jimenez et al., 2015). In addition, some countries have successfully implemented AD into large-scale applications (Rasheed et al., 2016).

In China, more than 100 million tons of fruit and vegetable residues are abandoned annually (Scano et al., 2014). Owing to their properties of high moisture and organic contents, fruits residues will easily deteriorate even for short–term disposal, which will breed mosquitoes, spread disease, and cause other environmental complications. They will also constitute a nuisance in municipal landfills since a lot of leachate will be produced and the cost is relatively high (Garcia-Peña et al., 2011; Scano et al., 2014). AD seems quite suitable for reusing fruit residues. However, to our surprise,

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the scientific literature only contains a few studies on AD of fruit residues. Except for some research on the anaerobic biodegradability (BD) of common fruit residues such as those of bananas, mangos, and oranges (Martín et al., 2010; Tumutegyereize et al., 2011), most reported studies probe into co-digestion of fruit residues and other substrates such as crop stalks, vegetable wastes, and different manures (Habiba et al., 2009; Fei et al., 2013; Suryawanshi et al., 2013; Fonoll et al., 2015). There remain many types of fruit residues that have high annual production but have never been considered for continuous or batch anaerobic digestion. The abandonment of fruit residues is not only a large problem to the environment but also a great waste of the world's resources. Thus, thorough and deep research on batch AD tests of various fruit residues as a single substrate is urgently needed, and it is of great significance to explore the potential correlation between the experimental methane yield and the organic compositions of fruits residues to provide guidance on the conversion of new biomass residues to clean energy products.

Predicting behaviors and optimizing the process of anaerobic system by understanding the kinetics of the methane production process are fundamental for the design of anaerobic digesters. Although a large amount of work to simulate and model the discontinuous AD process has been performed, it has mostly been based on first-order or modified Gompertz models (Gavala et al., 2003; Kythreotou et al., 2014; Batstone et al., 2015). Limited literature using other models such as the Cone and Fitzhugh models or exploring new modeling approaches, is available (El-Mashad, 2013; Brulé et al., 2014). Additionally, there exist large differences in experimental conditions, operations, and feedstock, so the reliability of the said models could vary greatly (Zhen et al., 2015). Hence, a careful comparison of different kinetic models on the discontinuous AD process of fruit residues is necessary.

The objectives of this study were to: (1) compare the AD performance of 17 types of fruit residues (mostly never tried for AD) as a single substrate using a simple and unified method (anaerobic batch test); (2) comprehensively investigate and analyse the characteristics of these fruit residues and explore the correlation between the experimental methane yield and the organic components using multiple linear regression model (MLRM); and (3) evaluate and compare different kinetic models for the batch AD process of fruit residues.

2. Material and methods

2.1. Substrates and inoculum

Seventeen types of fruit residues, including peels, seeds, and shells, were selected. Fresh fruits were purchased from markets in Beijing, China. All samples were ground to a particle size of approximately 5 mm using a blender (JOYOUNG, China), with the exception of the shell of durian, which was ground by a high-speed grinder (XINGSHILIHE, China) because of its hardness. Ground samples were stored at 4 °C for several days before characteristic analysis and discontinuous AD were performed. Anaerobic sludge taken from Beijing Donghuashan Biogas Plant where only pig manure was fed as a substrate was used as inoculum. The sludge was taken once 2 months and stored in barrels at room temperature. Before batch AD tests, the supernate of the sludge was removed. The precipitate was used as the inoculum and added to the digester according to the substrate to inoculum ratio. The TS and VS of the inoculum was measured to be 5.07% and 4.33%. Cellulose, hemicelluloses, and lignin contents were tested using an AMKOM 2000 fiber analyser (AMKOM, USA). Lipid, protein, and non-structural carbohydrates contents were measured using Soxhlet extraction, Bradford assays, and the DNS method, respectively (Teixeira et al., 2012; Li et al., 2013c; Liang and Li, 2013). VFA was measured using a gas chromatograph (Agilent 7890A, USA) with an FID detector according to a reported method (Li et al., 2013c).

2.2. Biomethane potential

Discontinuous anaerobic digestion was carried out using 500 ml bottles as reactors. The schematic shape was shown in Supplementary material. The organic loading in every reactor was set to 6 g VS/L with a substrate to inoculum ratio (S/I) of 1. After the required amount of substrates and inoculum were added, pure water was added to a working volume of 250 ml. Before the reactors were closed with rubber plugs and screw caps, an anaerobic atmosphere was created inside the bottles by blowing nitrogen for 1 min. The reactors were then placed into an incubator at a constant temperature of 37 °C. Each sample had two bottles. Two blank bottles containing 6 g VS/L of inoculum with the same working volume were also used as a correction for background methane production.

The pressure in the headspace of each reactor was measured using a 3151 WAL-BMP-Test system pressure gauge (WAL Mess- und Regelsysteme GmbH, Germany) at a fixed time everyday. The biogas in the digester was released under water to prevent gas exchange between the reactor and the ambient atmosphere. The pressure was measured again. The biogas yield was calculated using the ideal gas law (El-Mashad and Zhang, 2010): $V_{biogas} = \Delta P \times V_{head} \times C/(R \times T)$, where V_{biogas} represents the daily biogas volume (L), ΔP stands for the absolute pressure difference (mbar), V_{head} is the volume of the head space (L), C refers to the molar volume (22.41 L/mol), T is the absolute temperature (K), and R represents the universal gas constant (83.14 L mbar/K/mol) (Li et al., 2013b). The biogas components were analysed using gas chromatography (Agilent 7890B, USA).

2.3. Maximum methane potential and biodegradability

To predict the maximum methane yield and compare the methane production performance of different substrates, two typical methods to calculate the maximum methane potential (MMP) were selected here (Li et al., 2013c). One method was based on the elemental composition (expressed as MMP_{ele}), as shown in Eqs. (1) and (2).

$$C_nH_aO_bN_c + \left(n - \frac{a}{4} - \frac{b}{2} + \frac{3c}{4}\right)H_2O \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8}\right)CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4} + \frac{3c}{8}\right)CO_2 + cNH_3 \quad (1)$$

$$MMP_{ele}\left(\frac{\text{mL CH}_4}{\text{g VS}}\right) = \frac{22.4 \times 1000 \times \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8}\right)}{12n + a + 16b + 14c} \quad (2)$$

The other was based on the organic composition (expressed as MMP_{org}), as seen in Eq. (3).

$$MMP_{org}\left(\frac{\text{mL CH}_4}{\text{g VS}}\right) = (373VFA + 496Protein + 1014Lipids + 415Carbohydrates + 727Lignin)/100 \quad (3)$$

where VFA ($C_2H_4O_2$), lipids ($C_{57}H_{104}O_6$), protein ($C_5H_7NO_2$), lignin ($C_{10}H_{13}O_3$) and carbohydrates ($C_6H_{10}O_5$) are percentages of VS (Li et al., 2013c).

BD was determined by experimental methane yield (expressed as EMY) and MMP according to the following equations: $BD_{ele} = EMY/MMP_{ele}$; $BD_{org} = EMY/MMP_{org}$ (El-Mashad and Zhang, 2010).