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Research article

Enhancing anaerobic digestion of high-pressure extruded food waste by inoculum optimization

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The inoculation for extruded food waste anaerobic digestion (AD) was optimized to improve methane (CH_4) yield. The inoculum of acclimated anaerobic sludge resulted in high biodegradability, producing CH_4 yields from 580 mLCH_4 $g^{-1}\cdot VS_{added}$ to 605 mLCH_4 $g^{-1}\cdot VS_{added}$, with corresponding BD_{CH4} ranging from 90% to 94%. We also investigated inoculum to substrate ratios (ISRs). With regards to digested slurry as inoculum, we found that a decrease in ISR improved CH_4 yield, while a lower ISR prolonged the lag time of the initial AD stage due to lipid inhibition caused by excessive food waste. These results demonstrate that minimal inocula are required to start the AD system for high-pressure extruded food waste because it is easily biodegraded. High ammonia concentration had a negative effect on CH_4 production (i.e., when free ammonia nitrogen [FAN] increased from 20 to 30 mg L^{-1} to 120–140 mg L^{-1}, the CH_4 yield decreased by 25%), suggesting that FAN was a significant inhibitor in CH_4 yield reduction. In terms of CH_4 yield and lag time of the AD process, the optimal inoculation of digested slurry for the extruded food waste had an ISR of 0.33 with CH_4 yield of 505 mLCH_4 $g^{-1}VS_{added}$, which was 20% higher than what was found for higher ISR controls of 2, 1 and 0.5.

1. Introduction

With the rapid development of catering services in China, the amount of food waste has been increasing significantly. In 2014, the amount of food waste generated in Beijing was approximately 2000 tons per day. In general, food waste is easily biodegradable using anaerobic digestion (AD) because of high water, fat, protein, and crude fiber contents (Zhang et al., 2007). However, food wastes contain many items that cannot be readily biodegradable, including dinner residues, kitchen waste, plastic bags, chopsticks, and inorganic matter. Thus, it is necessary to effectively separate these difficult-to-degrade substances from the biomass mixtures to enhance the methane (CH_4) production potential of the digested substrates.

High pressure extrusion, as a mechanical pretreatment method, can effectively enhance separation efficiency and improve CH_4 production yield in substrate digestion (Chen et al., 2014; Novarino and Zanetti, 2012). Raw materials are placed onto screen drums and extruded under high pressure. The organic fraction of the raw materials is discharged through the drum holes and can be used for AD, while the non-organic parts remain in the drum. In this process, multiple operations are likely combined in an extruder, including frictional heating, material mixing, particle size reduction, and shearing (Hjorth et al., 2011).

Elbeshbishy et al. (2012) explored the highest CH_4 yield of food waste with two different inocula – Toronto's inoculum and Guelph's inoculum, both of which are mesophilic anaerobic digester, but treating wastewater and organics from food waste respectively. The highest CH_4 yield was 790 mLCH_4 $g^{-1}VSS_{added}$ at an S/X of 0.5 g $COD_{substrate}$/g$VSS_{inoculum}$ with Toronto's inoculum. By contrast, for Guelph's inoculum, the maximum value of 1400 mLCH_4 $g^{-1}\cdot VSS_{added}$ at an S/X of 0.25 g $COD_{substrate}$/g$VSS_{inoculum}$. Tests of food waste anaerobic digestion report a wide range of CH_4 yields in different studies; a high CH_4 yield of 435 mLCH_4 $g^{-1}\cdot VS_{added}$ was obtained by Kawai et al. (2014), but the

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maximum value of CH_4 yield reported in Liu's study (2013) is around 350 mLCH_4 $g^{-1}VS_{added}$. Besides the food waste compositions differ between studies, variations in inoculum sources and inoculum concentrations may also contribute to a wide range of CH_4 yields.

Inoculation is crucial for AD, especially during system startup (Motte et al., 2013). Although the residues from anaerobic reactors are generally considered the optimal inoculum, excess sludge from secondary sedimentation tanks also contains anaerobic microflora because of inundation and long hydraulic retention times. For these reasons, researchers have begun to utilize excess sludge as an inoculum source (Wang et al., 2014).

The inoculum-to-substrate ratio (based on wet materials) has important implications to the anaerobic system. Many researchers have examined the optimal ISRs (VS ratio); however, results are inconsistent, likely due to the different properties of substrates and inocula. It is reported that too low of an ISR may result in a toxic effect but too high of an ISR may prevent enzyme induction (Elbeshbishy et al., 2012). Li et al. (2014) investigated the AD of microalgae residues and reported that the highest CH_4 yield (210.6 mLCH_4 $g^{-1}VS_{added}$) was obtained at a ISRs of 3. However, using microalgae AD, Alzate et al. (2012) showed that the optimal ISR was 2 and maximum CH_4 production yield reached 395 mLCH_4 $g^{-1}VS_{added}$.

Although there are many reports on food waste AD, most studies have either assessed anaerobic co-digestion with other wastes (Agyeman and Tao, 2014; Liu et al., 2013) or assessed different pretreatment methods on improving CH_4 yield of raw materials (Hjorth et al., 2011; Elbeshbishy and Nakhla, 2011; Gadhe et al., 2014). However, there have been few reports on the effect of optimizing inoculation on the AD of pretreated food waste. Forster-Carneiro et al. (2008) investigated the effect of inoculum contents in food waste dry AD reactors, and the results showed that at the TS of 20% and 30% of inoculum source was the optimal condition due to highest VFAs production.

The objective of the study was to investigate CH_4 yield from high-pressure extruded food waste, as well as the volatile solid and soluble chemical oxygen demand removal efficiencies using various inocula and ISRs. These results may provide a better understanding of the effects of inoculation for mechanically pretreated substrates.

2. Materials and methods

2.1. Raw materials

Food waste was derived from the Dongcun solid waste treatment plant (Beijing), which collects food waste from restaurants in the city. In the study, high-pressure extrusion with hydraulic pressure (pressure of approximately 35 Mpa) was used as a pretreatment method to separate difficult-to-degrade substances from the raw materials. The extruded substrate was in a slurry state (particle size less than 16 mm) with large specific surface area and was highly homogenous and biodegradable. S2 summarizes the component composition analysis of the extruded fractions.

2.2. Inoculum

Three different inocula were selected. The source of inoculum A was excess sludge (TS = 3.2%, VS/TS = 84.3%) from a secondary sedimentation tank in a sewage water treatment plant in Beijing. Inoculum B was a digested slurry (TS = 1.92%, VS/TS = 43%) with a high ammonia concentration (4000 mg L^{-1} to 5000 mg L^{-1}) from a well-operated anaerobic reactor that had been used to digest chicken manure. Inoculum C was an acclimated anaerobic sludge (TS = 2.84%, VS/TS = 42.7%). Inoculum C was cultivated from inoculum A in anaerobic conditions using extruded food waste as a substrate until the CH_4 ceased to be generated (less than 20 mL per day).

Background CH_4 production from the various inocula was determined in blank assays (without substrate). These values were then subtracted from those of CH_4 production obtained in assays including the substrate (Zhou et al., 2013).

2.3. Analytical methods

Standard methods (APHA, 2005) were used to analyze TS and VS, as well as determining the salt content of the substrate and inocula. After the suspended solid was separated in the digester effluent through centrifugation at 3000 rpm for 10 min, the liquid supernatant was filtrated through a 0.45 μm membrane before total ammonia nitrogen (TAN) and soluble chemical oxygen demand (SCOD) were measured. TAN was determined using the method of Nessler's reagent spectrophotometry at 420 nm (MEP, 2002). SCOD was analyzed using the HACH method. Elemental analysis of the substrate was measured by an elemental analyzer (PerkinElmer, CE-440, USA). pH was measured directly with a pH meter (Mettler, fe20, Switzerland). The concentrations of ammonium ion (NH_4^+) and free ammonia nitrogen (FAN) were determined as reported previously (Siles et al., 2010).

The component compositions of the extruded substrate, such as lipid, protein, carbohydrate, and crude fibers, were analyzed after the substrate was dried at 105 °C at an authorized laboratory of the Ministry of Agriculture of China.

2.4. Batch experiments

The AMPTS II system (Bioprocess Control, Sweden) was used for rapid and accurate online measurements, by which duplicates of 0.5 L reactors were conducted for each reaction. The system consisted of three units: Unit A, a water bath maintained at mesophilic temperature (35 °C) with 15 glass bottles for AD; Unit B, a non-CH_4 gas adsorption unit, including carbon dioxide and hydrogen sulfide with 15 bottles of 80 mL sodium hydroxide (NaOH) of 3 M; and Unit C, in which the volume of CH_4 released from Unit A was automatically recorded. A mixing rod with slow mechanical rotation was used in each bottle in Unit A. The rotation consisted of 120 s of stirring and was stopped for 60 s stop for one round. As each test duration was determined by the biodegradability of the substrate, the test was not completed until the CH_4 generation was less than 20 mL per day.

The modified Gompertz model (Equation (1)) was used to describe CH_4 generation during AD (Liu et al., 2013; Gadhe et al., 2014).

$$H = P \cdot exp\left\{-exp\left[\frac{R_m \cdot e}{P}(\lambda - t) + 1\right]\right\} \quad (1)$$

The parameters of P, R_m, and λ for each reaction can be determined by fitting the experimentally measured data into Equation (1) with the software MATLAB 2008a.

3. Results and discussion

3.1. CH_4 yield of extruded food waste

Based on the element analysis, the stoichiometric equation of the extruded food waste was determined to be $C_{16}H_{28.2}O_{7.3}N$. The entire AD process of waste expressed as Equation (2) and the theoretical CH_4 potential could be calculated using the Buswell formula (Equation (3)) (Raposo et al., 2011), as follows: