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Biodegradation of particulate organics and its enhancement during anaerobic co-digestion of municipal biowaste and waste activated sludge

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A B S T R A C T

Biodegradation of particulate organics is considered to be as an essential factor in the anaerobic co-digestion performance and biogas recovery of biowaste. To determine the rate-limiting step of particulate organics hydrolysis during co-digestion of municipal biowaste and waste activated sludge (WAS), the particle size distribution of organic compounds before and after digestion was examined for a mesophilic co-digestion system. As organic load rate increased and hydraulic retention time decreased, the removal rate of big-size particulate organics did not change significantly, indicating that the disintegration of big particles is not the rate-limiting step, while soluble organics accumulated in the digestate. This implies that the enzymatic hydrolysis of soluble organics is the rate-limiting step in the hydrolysis process. Addition of WAS to substrate did not significantly change the removal rate of particulate organics >420 μm, while the residual content of particulate organics 0.45–74 μm in size increased because the non-biodegradable organics in WAS were in this size range. After biodegradability enhancement of WAS by hydrothermal pretreatment, the removal rate of particulate organics increased significantly. Thus, biodegradability enhancement is more effective than particle size reduction in optimizing the co-digestion process with WAS in practice.

1. Introduction

The treatment and disposal of municipal biowaste (MBW, e.g., restaurant food waste, fruit and vegetable residues) and waste activated sludge (WAS) from municipal wastewater treatment plants is a major problem in almost all cities in China; the total quantity of these 3 kinds of MBW is more than 50 million tons annually. Anaerobic digestion (AD) is the top choice for treatment of MBW in consideration of stabilization of wastes and energy recovery [12]. AD is a biological process that converts organic matter into a mixture of carbon dioxide and methane gases by a complex community of microorganisms. It has been used in the treatment of many kinds of organic wastes, such as kitchen waste, grass residues, and animals manure. Taking the variety of the substrates and the versatility of the facilities into account, MBW co-digestion with municipal sewage sludge is always used; this process has the advantage of providing a potential increased output of biogas, and stability of the anaerobic system [11].

The characteristics of raw biowaste materials used in this study are shown in Table 1. Characteristics measured were the solid fraction, organic composition, and elemental composition. Suspended solids (SS), which include both organic and inorganic particulate solids, showed a high particulate solid content in raw materials. Volatile solids (VS), standing for organic matter, accounts for 65%–90% of the total solids (TS). VS can be divided into volatile dissolved solids (VDS) and volatile suspended solids (VSS). VSS/VS, representing the particulate organic solid ratio in the organic fraction, accounts for 46.2%, 58.3% and 96.6% of the restaurant food waste (RFW), fruit and vegetable residues (FVR), and WAS, respectively, indicating that particulate organic compounds play an important role in the AD process. This is in agreement with other studies that have demonstrated that the concentration of particulate organic compounds is the essential rate-limiting factor of AD process [18,20]. The concepts of disintegration, solubilisation, and

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Table 1
Characteristics of raw biowaste materials.

	Restaurant food waste	Fruit and vegetable residues	Waste activated sludge
Water content (%)	83.4	93.8	84.5
TS (g/L)	166.3 ± 26.7	62.2 ± 16.0	154.9 ± 18.1
VS (g/L)	149.0 ± 24.3	50.8 ± 11.2	101.9 ± 10.8
SS (g/L)	72.8 ± 14.3	35.7 ± 14.2	151.7 ± 21.4
VSS (g/L)	68.8 ± 12.0	29.6 ± 11.2	98.5 ± 12.8
VS/TS (%)	89.6	81.6	65.8
VSS/VS (%)	46.2	58.3	96.6
Crude fat (%TS)	21.8	2.89	10.25
Crude protein (%TS)	16.8	13.2	34.3
Crude fiber (%TS)	5.58	15.31	7.09
C (%)	48.2	42.0	37.2
H (%)	7.3	6.1	5.5
N (%)	2.8	2.4	5.9
C/N	17.4	17.4	6.3

enzymatic hydrolysis are usually expressed by the general kinetic term of particulate organic compounds hydrolysis in most of the literature [2]. Particulate carbohydrates, proteins, and lipids, as well as particulate and soluble inert material, are the products of the disintegration of composite materials. Monosaccharides, amino acids, long chain fatty acids, and glycerol are the products of the enzymatic degradation of particulate carbohydrates, proteins and lipids, respectively, and microorganisms benefit from the soluble products and produce the corresponding hydrolytic enzymes [17]. Theoretically, the disintegration of composites to particulate constituents and the subsequent enzymatic hydrolysis to their soluble monomers are both extracellular processes. Degradation of soluble materials is mediated by organisms intracellularly, resulting in biomass growth and subsequent decay [3]. It is unclear which process (disintegration, solubilisation, or enzymatic hydrolysis) is the primary rate-limiting step in AD process. In this study, the removal rate of particulate organic materials of different particle sizes is used to elucidate the rate-limiting step of particulate organics hydrolysis.

Generally, pre-treatment methods are introduced to help reduce the effect of the rate-limiting factor. The main effects that pretreatment has on different substrates, as reported in the literature, can be identified as (i) particle size reduction, (ii) solubilisation, (iii) biodegradability enhancement, (iv) formation of refractory compounds, and (v) loss of organic material [5]. Many studies explore the correlation between particle size reduction and solubilisation, and the enhancement of biodegradability. The reported correlations in the literature are ambiguous; in some cases the biodegradability enhancement of the substrate is strongly correlated to the solubilisation or particle size reduction [19], in others the correlation is lacking or even negative [6,16] Izumi et al. [9]. reported a methane yield increase of 28% when the mean particulate size decreased from 0.89 to 0.72 mm, but when particle size was <0.51 mm, the methane yield decreased as a result of high VFA accumulation in the anaerobic digester Silvestre et al. [15]. found that reducing the particle size of the organic fraction of municipal solid waste from 20 to 8 mm did not significantly improve the gas yield or the production rate in a co-digestion system with sewage sludge.

Therefore, the value of the option to include pre-treatment in the design of a project becomes difficult to assess because of uncertainty about the effect of particle size reduction on the biodegradation process. In this study, the correlation between biodegradability enhancement and particle size reduction for biowaste is addressed, and a potential option for biodegradability enhancement of WAS is proposed for anaerobic codigestion.

2. Materials and methods

2.1. Materials

RFW is produced in higher quantities than FVR and WAS in China. It has been reported that a WAS content of 10%–30% can improve AD performance and stability [4,7]. In the present study, the model substrate (Substrate A) used was composed of 50% RFW, 25% FVR, and 25% WAS. RFW was collected from a student canteen (seating capacity of over 1000) at Tsinghua University, Beijing. FVR was obtained from a wholesale market, and WAS was obtained from a municipal wastewater treatment plant in Beijing (Qinghe WWTP; Northern Beijing; capacity: 400,000 m^3 d^{-1}). The inert materials in RFW and FVR were manually separated (e.g., plastic, bone, wood, and others). RFW and FVR were crushed initially by a RFW pulverizer to less than 3 mm together at a ratio of 2:1. The pulverized material was then mixed with WAS at a ratio of 3:1. The mixed feedstock was kept at 4 °C before use. Two more substrates with no WAS (Substrate B) and 60% WAS (Substrate C) were used to address the effects of feedstock. Table 2 presents the general chemical properties of the substrates in terms of solid fraction and organic composition.

2.2. AD systems

The research on the effects of the organic load rate (OLR) on AD performance was carried out in a continuous stirred-tank reactor with an actual volume of 2 m^3 and an effective volume of 1.6 m^3. The research on substrate B and substrate C was carried out in two continuous stirred-tank reactors with an actual volume of 220 L and an effective volume of 170 L. Both the 2-m^3 and 220-L reactors were operated under mesophilic conditions at 35 °C ± 2 °C, heated by a water jacket. The reactors were mixed using mechanical stirrers (100 rpm) with an agitation time of 10 min per 2 h, and were fed once a day using a screw pump. The inoculums of the 2-m^3 reactor were collected from another municipal wastewater treatment plant (Xiaohongmen WWTP, located in southern Beijing), where the excess sewage sludge was treated by AD.

The TS, SS, VS, and VSS contents were used to characterize the solid composition of the biowaste. TS represents all the components of the biowaste except for water TS can be divided into dissolved solid (DS) and SS according to its existing phase, or into VS and fixed solid (FS) according to its composition. The quantitative relationships are shown below:

$$TS = SS + DS = VS + FS \quad (1)$$

The TS, SS, VS, and VSS concentrations of the inoculums were