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Activated carbon enhanced anaerobic digestion of food waste – Laboratory-scale and Pilot-scale operation

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ABSTRACT

Effects of activated carbon (AC) supplementation on anaerobic digestion (AD) of food waste were elucidated in lab- and pilot-scales. Lab-scale AD was performed in 1 L and 8 L digesters, while pilot-scale AD was conducted in a 1000 L digester. Based on the optimal dose of 15 g AC per working volume derived from the 1 L digester, for the same AC dosage in the 8 L digester, an improved operation stability coupled with a higher methane yield was achieved even when digesters without AC supplementation failed after 59 days due to accumulation of substantial organic intermediates. At the same time, color removal from the liquid phase of the digestate was dramatically enhanced and the particle size of the digestate solids was increased by 53% through AC supplementation after running for 59 days. Pyrosequencing of 16S rRNA gene showed the abundance of predominant phyla *Firmicutes*, *Elusimicrobia* and *Proteobacteria* selectively enhanced by 1.7-fold, 2.9-fold and 2.1-fold, respectively. Pilot-scale digester without AC gave an average methane yield of 0.466 $L\cdot(gVS)^{-1}\cdot d^{-1}$ at a composition of 53–61% v/v methane. With AC augmentation, an increase of 41% in methane yield was achieved in the 1000 L digester under optimal organic loading rate (1.6 g $VS_{FW}\cdot L^{-1}\cdot d^{-1}$).

1. Introduction

Ever-increasing municipal solid waste (MSW) disposal in megacities is a critical global issue (Srivastava et al., 2015). Among the major organic fractions of MSW is food waste (FW), which is generated annually at an exponential rate and a low recycling rate (Kiran et al., 2014; Lin et al., 2013). Anaerobic digestion (AD) has been touted as a promising strategy to achieve FW treatment and bioenergy recovery simultaneously (Pham et al., 2015). In the AD process, organic materials like polysaccharides, proteins and lipids are degraded by a consortium of microorganisms, in the absence of oxygen, resulting in the production of methane-rich biogas (Li et al., 2016). However, during practical AD operations, several critical technical problems, including low biogas productivity and poor operation stability due to acidification of FW (Jiang et al., 2012), and undesired digestate color (Marcilhac et al., 2014) need to be addressed for increased AD efficiency.

In order to enhance AD performance, various strategies including feedstock pretreatment, parameter optimization, additive supplementation, etc. have been tested, among which additive strategy exhibited several advantages. These include easy application, no need to modify current infrastructure, and at an economical operation cost (Romero-Güiza et al., 2016). One effective additive is activated carbon (AC). AC is an amorphous carbonaceous material, which serves as a good immobilization matrix for enhanced bacteria growth (Weber et al., 1978); larger bacteria community translates to more methane production (Fagbohungbe et al., 2017). Simultaneously, AC has high adsorption capability and potential enhancement of direct interspecies electron transfer for microorganisms (Lee et al., 2016; Zhao et al., 2016). In addition, low cost AC with high surface area can be easily prepared via steam activation from char, a byproduct from the gasification of woody biomass wastes (Maneerung et al., 2016). So far, AC, as an additive, has been successfully utilized in AD to enhance process efficiency in wastewater treatment (Malik, 2004; Monser and Adhoum, 2002; Skouteris et al., 2015). It was anticipated that augmentation with AC could potentially improve the AD of FW for higher methane yield, better operation stability and effective color removal of the liquid phase of AD digestate.

The overall objective of this research was to investigate the effects of adding AC to AD digesters to treat FW. This was accomplished in various sizes of digesters - 1 L, 8 L and a pilot-scale 1000 L. Lab-scale and pilot-scale AD tests can provide data for scale-up of digester operation from lab-scale to industrial scale

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(Kowalczyk et al., 2011). Previously, pilot-scale AD studies using diverse feedstocks including rice straw (Mussoline et al., 2013), kitchen waste and fruit/vegetable waste (Fiore et al., 2016; Wang et al., 2014b), bio-waste fraction from domestic wastes (Gallert et al., 2003), waste activated sludge (Liu et al., 2012b) and manure (Kaparaju et al., 2008, 2009) have been reported. Hitherto, most pilot-scale studies focus on parameter optimization in traditional AD operation, and there is still room for improvement of methane yield compared to the ideal productivity (Zhang et al., 2017c). To the best of our knowledge, effect of AC supplementation on the performance of pilot-scale AD operation has not been reported.

The optimum dosage of AC needed was obtained through a 1 L lab-scale digester. Subsequently, the same AC dosage was applied to the larger digesters. The effects of AC supplementation on methane production and operation stability were elucidated in 8 L lab-scale digesters. Removal of color in the liquid phase of the digestate and particle size distribution of digestate solids with and without AC supplementation were also investigated. To better understand the enhancement mechanism of AC supplementation, quantification of total bacteria and archaea by real-time PCR and biodiversity and taxonomy analyses of bacterial communities through high throughput 16S rDNA gene pyrosequencing were conducted. Finally, the improved efficiency of AC supplementation was validated in a 1000 L pilot-scale digester.

2. Materials and methods

2.1. Substrate, seed sludge and additive

FW collected from a canteen of the National University of Singapore was utilized as feedstock. Raw FW mainly included rice, vegetables, meat, noodles and condiments. To avoid blocking of feeding tubes, indigestible compositions like chopsticks and plastics were manually removed before the FW was homogenized in a kitchen blender. The homogenized FW was sub-packaged into small containers with different amounts according to the OLR before being stored at −20 °C. All the feedstock underwent the freeze-thawing process only once and no significant difference ($p > 0.05$) was found in the main characteristics (pH, TS, VS, C/N ratio and elemental composition) of original FW and freeze-thawed FW. Seed sludge was collected from an industrial scale anaerobic digester treating waste activated sludge in the Ulu Pandan Water Reclamation Plant in Singapore. Characteristics of FW and seed sludge used for AD are presented in Table 1. The analytical grade AC used in this experiment was purchased from Tianjin ZhiYuan Reagent Co., Ltd. The bulk density, surface area and particle size of AC are 564 kg/m^3, 385 m^2/g and 0.037–0.149 mm, respectively.

2.2. Lab-scale experiments (1 L)

In the 1 L lab-scale study, five digesters, indicated as A1, A2, A3, A4 and A5 corresponding to 0, 6, 12, 18 and 24 g AC addition, respectively, were used to determine the optimum AC dosage with respect to enhanced methane production. The AD process was conducted in the 1 L digesters at 0.8 L working volume. These glass digesters were equipped with a 300 rpm stirrer and operated in a semi-continuous mode (feeding once per day) on magnetic stirring apparatus. The organic loading rate (OLR) was gradually increased from 1.4 to 5.5 g $VS_{FW}{\cdot}L^{-1}{\cdot}d^{-1}$. A 3 L gas sampling bag was connected to the outlet of each digester for collecting the biogas. All digesters were operated at 37 °C within a constant temperature and humidity incubator. Initially, identical 0.8 L seed sludge was added into each digester. After a 3-day start-up period, the necessary amount of AC was added into each digester. Digester A1 without AC addition was the control digester. All the digester experiments were conducted in triplicates under the same experimental conditions. The volume and concentration of the biogas obtained from each digester were determined daily.

Table 1
Characteristics of FW and seed sludge used for AD.

Characteristics	Units	FW	Seed sludge
Extractives	wt.%	97.93 ± 3.16	–
Cellulose	wt.%	0.52 ± 0.03	–
Hemicellulose	wt.%	1.46 ± 0.05	–
Lignin	wt.%	<0.10	–
pH	–	6.29 ± 0.13	7.03
Total solids (TS)	wt.%, wet basis	28.60 ± 0.08	1.68 ± 0.09
Volatile solids (VS)	wt.%, wet basis	27.42 ± 0.13	1.11 ± 0.03
VS/TS ratio	–	0.96 ± 0.01	0.61–0.72
Soluble COD	mg/L	–	271.27 ± 36.58
Volatile fatty acids (VFAs)	mg COD/L	–	29.04 ± 5.81
C	%/TS	54.23 ± 0.25	–
N	%/TS	3.13 ± 0.07	–
C/N	–	17.33 ± 0.02	–
H	%/TS	7.39 ± 0.15	–
S^{2+}	%/TS	<0.50	–
K^{+}	%/TS	0.42 ± 0.01	–
Na^{+}	%/TS	0.96 ± 0.02	–
Ca^{2+}	%/TS	0.65 ± 0.01	–
Mg^{2+}	%/TS	0.11 ± 0.0	–
Fe^{3+}	%/TS	<0.10	–
Zn^{2+}	%/TS	<0.10	–
Al^{3+}	%/TS	0.10 ± 0.0	–
Cu^{2+}	%/TS	<0.10	–

2.3. Lab-scale experiments (8 L)

Fig. 1 shows the (A) lab-scale experimental set-up (8 L) for semi-continuous AD and (B) pilot-scale experimental set-up for continuous digestion. As shown in Fig. 1(A), the main body of the digester was made of tempered glass, which was convenient to observe liquid level and mixing situation. Each digester was coupled with an individual agitator motor for agitation and a thermocouple for heating, which could be controlled to the desired set points through a control panel. A wet gas meter was connected to the outlet of each digester for monitoring the daily biogas flux. Upon exiting the gas meter, the biogas was collected in a 10 L gas sampling bag, which was used for determining methane concentration. The lab-scale tests were conducted in a semi-continuous mode in mesophilic conditions (370C) using six identical digesters (8 L total volume, 5 L working volume). Three digesters supplemented with AC under optimum dose condition derived from the 1 L optimization experiment were used as experimental group (hereafter referred to as R1) while another three digesters without AC were used as the control group (hereafter referred to as R2). Results from the three digesters in each group were averaged as representative data for that group, R1 or R2. Initially, all digesters were inoculated with 5 L homogenized seed sludge. Identical daily feeding was applied to all digesters with stepwise increasing OLR from 1.1 to 2.2, 3.3, and 4.4 g $VS_{FW}{\cdot}L^{-1}{\cdot}d^{-1}$. Before feeding, an equal volume of effluent was taken through the feeding hole of the digester using a sampling tube. The agitation speed was set at 300 rpm. During the AD operation, biogas volume, methane concentration, pH, and soluble chemical oxygen demand (SCOD) were monitored dynamically. After centrifugation and filtration, the effect of AC on color change of the liquid phase of the digestate was also assessed. Seed sludge and sludge samples from R1 and R2 were taken for analyzing microbial community structure through real-time PCR and high throughput 16S rDNA gene pyrosequencing.

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