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Technical note

Pilot-scale anaerobic co-digestion of municipal biomass waste: Focusing on biogas production and GHG reduction

Xiao Liu [a,*], Xingbao Gao [a,b], Wei Wang [a], Lei Zheng [a], Yingjun Zhou [c], Yifei Sun [d]

[a] School of Environment, Tsinghua University, Beijing 100084, China
[b] Chinese Research Academy of Environmental Sciences, Beijing 100012, China
[c] Department of Urban and Environmental Engineering, Graduate School of Engineering, Kyoto University, Katsura, Nisikyo-ku, Kyoto 615-8540, Japan
[d] School of Chemistry and Environment, Beihang University, Beijing 100191, China

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ABSTRACT

A pilot-scale anaerobic co-digestion research study is presented to elucidate the feasibility of developing anaerobic digestion (AD) as an effective disposal method for municipal biomass waste (MBW) in China, focusing on biogas production and greenhouse gas (GHG) reduction. Food waste, fruit–vegetable waste, and dewatered sewage sludge were co-digested in a continuous stirred-tank reactor for biogas production. Stable operation was achieved with a high biogas production rate of 4.25 $m^3 (m^3 d)^{-1}$ at organic loading rate of 6.0 $kgVS (m^3 d)^{-1}$ and hydraulic retention time of 20 d. A total of 16.5% of lipids content was beneficial to the biogas production of the feedstock without inhibition to anaerobic digestion. Compared with the landfill baseline, GHG reduction is an important environmental benefit from MBW digestion. Therefore, anaerobic co-digestion is a promising alternative solution for MBW because it contributes significantly to the sound management of municipal solid waste in China.
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1. Introduction

With the rapid economic development and urbanization of China, almost all of its megacities are faced with the problem of municipal solid waste (MSW) disposal. In 2009, a total of 157.4 million tons of MSW was collected and transported nationwide. Of these, 89.0, 20.2, and 1.8 million tons were treated by landfill, incineration, and composting, respectively [1]. With increasing quantity, 50–60% of the MSW was biomass waste characterized by high water and biodegradable organic content. The municipal biomass waste (MBW) has led to serious adverse effects in traditional MSW treatment systems (i.e. landfill and incineration). The high water content may cause abundant production of leachate for landfill, and may cause unstable burning conditions and dioxin release from incineration. Also the high biodegradable organic content may cause the production and emission of greenhouse gas (GHG). From 2005 to 2010, the wastewater treatment capacity in China has increased from 60 million tons to 125 million tons which has resulted in the rapid increase of sewage sludge and the disposal of sewage sludge has also been a big problem in almost all the cities in China. In some cities, the sewage sludge is simply deposited onto the wasteland without any treatment, which has caused serious pollution. Efficient MBW management technology is increasingly required due to environmental and economical concerns, such as climate change, eutrophication, and the diminishing resources of fossil energy and raw materials.

Anaerobic digestion (AD) is considered as a sustainable option for the management of biomass wastes because the production of renewable energy and the recycling of nutrients [2]. Additionally, MBW separated from MSW and treated with AD can significantly reduce the load of traditional disposal facilities, and subsequently prolong their service life. It also decreases the secondary pollutants originated from the biodegradation of organic wastes during landfill, incineration and composting. AD has been employed in Western Europe since the 1980s, while up to 2010 one-hundred and ninety-five facilities have been constructed with a total annual capacity of 5.9 million tons [3]. De Baere concluded that AD facilities have captured the major market of waste treatment in the EU in the last decade, and will certainly continue developing in the future. AD is expected to become global utilised because of its environmental contribution, and energy benefits [4–6]. Co-digestion of different types of MBW has been discussed in many references due to its potential of increasing biogas output and improving stability of anaerobic system [4,7–10]. Co-digestion also means more feedstock supply, which is especially needed by large-

* Corresponding author. Tel.: +86 1062772814; fax: +86 1062782910.
E-mail addresses: liuxiaothu@gmail.com, liuxiao07@mails.tsinghua.edu.cn (X. Liu).

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scale plants where large quantities of MBW are required. Mata-Alvarez et al. summarized several cases of co-digestion of MBW, in both research and practical use [11].

Given that traditional technologies may cause severe environmental pollution for treating MBW, alternative environment-friendly treatment technologies of MBW are much needed in China. Meanwhile, renewable energy recovered from the biomass waste has become a global concern, and bioenergy has been listed in the Chinese New Energy Promotion Plan [12]. The AD of MBW can reduce the GHG emission in two respects: reduction as compared with the baseline management, and reduction through providing alternative resources in terms of non-renewable fossil energy and materials. In 2009, 79% of treated MSW was contributed by the landfill, and landfill is considered as one of the main GHG emission sources in current China [1]. The development of AD can restructure the traditional MBW treatment and disposal system in China, and in turn achieve the reduction of GHG emissions. Along with other advantages mentioned earlier, AD has attracted much attention of both government and enterprises in recent years, and it can be expected that AD will be widely used in the near future in China.

At present, the support policy from the central government has made every megacity receptive to building large-scale AD facilities in China. However, due to the differences of geographic locality and dietary habit, MBWs especially food waste in China has the typical characteristics of high water content (>85%) and high lipids content (>20% of dry basis) which is different from other countries, and few reports have discussed the AD of Chinese MBWs. Therefore, whether the Chinese MBWs fit for AD, and what is the suitable operation condition, these questions need to be answered before the construction and operation of the large-scale AD projects in China. Thus, a systematic research of AD of Chinese MBWs is urgently needed to provide fundamental technology parameters and promote the commercialization of AD technology. Finally, as the second biggest producer of carbon dioxide, China is facing great pressure in reducing GHG emissions, so the specific GHG reduction which can be achieved during AD of MBW is gaining interesting and needs to be quantified. In this study, a pilot-scale anaerobic co-digestion research is presented to elucidate the feasibility of developing AD in China as an effective disposal method for MBW, focusing on the system performance and biogas production, and then GHG reduction of AD was analyzed compared with landfill.

2. Methods

2.1. Raw materials

MBW used in this experiment comprised food waste (FW), fruit-vegetable waste (FVW), and dewatered sewage sludge (DSS). FW was collected from a student canteen (capacity, over 1000 students for a seated dinner) at Tsinghua University, FVW from a wholesale market, and DSS from a municipal wastewater treatment plant (WWTP) in Beijing (Qinghe WWTP; Northern Beijing; capacity, 400,000 $m^3\ d^{-1}$). The inert materials in FW and FVW were manually separated (e.g., plastic, bone, wood, and others). FW and FVW were crushed to less than 3 mm size firstly by a food waste pulverizer, and then mixed with DSS at the ratio of 2:1:1. The mixed feedstock was kept at 4 °C before use. During the experiment, a maximum of 80 $kg\ d^{-1}$ mixture was fed to the AD reactor.

The characterization of raw materials is shown in Table 1 in terms of solid content, organic composition, and elemental composition. Volatile solid (VS), standing for organic content, accounts for 65–90% of the total solid (TS). VS can be divided into volatile dissolved solid (VDS) and volatile suspended solid (VSS). VSS/VS, representing the organic solid ratio in organic fraction, accounts for 46.2%, 58.3% and 96.6% for FW, FVW, and DSS, respectively, indicating that organic solid plays an important role in the AD process, which has been proven to be the essential rate-limiting factor [13,14]. The organic compositions of the three raw materials differ significantly. For FW, the lipids content is the highest because of the Chinese traditional cooking style, whereas for FVW, the crude fiber is most abundant because of the cellulose content in fruits and vegetables. For DSS, the protein content is the highest compared with KW and VFR because of the high content of microorganisms. The C/N ratio of FW and FVW is suitable for AD; however, the C/N ratio of DSS is too low for AD. In the traditional AD of sewage sludge, slow degradation (>20 days), low organic loading rate, and the relatively low VS removal (30–40%) are often the disadvantages of the process because the digesters are operated with too low C/N ratios. Hence, in this study, DSS was co-digested with FW and FVW of higher C/N ratios to cover the adverse effects caused by its low C/N ratio.

Table 1
Characterization of raw materials.

	FW	FVW	DSS	Mixture (2:1:1)
Water content/%	83.4	93.8	84.5	88.7
Total solid/$g\ L^{-1}$	166.3 ± 26.7	62.2 ± 16.0	154.9 ± 18.1	142.1 ± 9.3
Volatile solid/$g\ L^{-1}$	149.0 ± 24.3	50.8 ± 11.2	101.9 ± 10.8	117.3 ± 7.8
Suspended solid/$g\ L^{-1}$	72.8 ± 14.3	35.7 ± 14.2	151.7 ± 21.4	91.7 ± 15.0
Volatile suspended solid/$g\ L^{-1}$	68.8 ± 12.0	29.6 ± 11.2	98.5 ± 12.8	74.0 ± 12.2
VS/TS/%	89.6	81.6	65.8	82.5
VSS/VS/%	46.2	58.3	96.6	63.1
Lipids/%TS	21.8	2.9	10.3	16.5
Protein/%TS	16.8	13.2	34.3	20.8
Crude fiber/%TS	5.6	15.3	7.1	6.4
C/%	48.2	42.0	37.2	45.4
H/%	7.3	6.1	5.5	6.6
N/%	2.8	2.4	5.9	3.5
C/N	17.4	17.4	6.3	12.9

2.2. Pilot-scale reactor start-up and operation

Continuous stirred-tank reactor (CSTR) was used in the research. The reactor had a volume of 2 m^3 (effective volume, 1.6 m^3; height, 2.7 m; and diameter, 1.0 m). The feedstock of the reactor was a mixture of 50% of FW, 25% of FVW and 25% of DSS in the percentage of weight.

Inoculums (digested sewage sludge) were collected from another municipal wastewater treatment plant (Xiaohongmen WWTP, located in southern Beijing), where the excess sewage sludge was treated by AD. A 1.6 m^3 volume of digested sludge was collected and pumped into the reactor. The TS, SS, VS, and VSS contents of the inoculums were 27.0, 25.0, 10.4, and 9.7 $g\ L^{-1}$, respectively.

The reactor was operated under mesophilic condition at 35 ± 2 °C by a water jacket. The reactors were constantly mixed using mechanical stirrers (100 rpm) with an agitation time of 15 min per two hours, and were fed once a day using a screw pump.

2.3. Analytical techniques

The analysis of TS, VS, SS and VSS were based on the Standard Analytic Methods promulgated by the National Environmental Protection Agency of China (1989). The measurement of crude fiber and protein were according to ISO 6865:2000 and ISO1871:2009, respectively. Lipids content was determined using soxhlet extraction method according to ISO 6492:1999. The samples were filtered through 0.45 μm filters before the measurement of volatile fatty acids (VFAs) using gas chromatography (SHIMADZU GC-2010) with

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