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Effect of temperature and organic loading rate on siphon-driven self-agitated anaerobic digestion performance for food waste treatment

Yong Hu [a], Takuro Kobayashi [a,*], Weikang Qi [b], Hiroshi Oshibe [c], Kai-Qin Xu [a,*]

[a] Center for Material Cycles and Waste Management Research, National Institute for Environmental Studies, Tsukuba 305-8506, Japan
[b] School of Chemical Engineering, Beijing University of Chemical Technology, Beijing 100029, China
[c] Solution Technology Department, Tokyo Gas Co., Ltd, Tokyo 105-8527, Japan.

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ABSTRACT

The effects of organic loading rate (OLR) and operating temperature on the performance of siphon-driven self-agitated anaerobic reactor (SDSAR) in an on-site food waste (FW) treatment system were investigated. Two reactors were operated in parallel for comparison between mesophilic condition (35 ± 1 °C) and thermophilic condition (55 ± 1 °C). With HRT above 15 d and OLR below 4.8 kg-COD/m^3/d, relatively high COD removal in the range of 84.5–92.3% was obtained in both reactors. The limits of the loading capacity of the mesophilic SDSAR were observed when OLR was further increased to 7.3 kg-COD/m^3/d by shortening HRT. Blocking and gas production reduction occurred and COD removal decreased sharply to 75.9% in the mesophilic reactor. In contrast, the thermophilic reactor can be operated at this OLR with satisfactory COD removal and biogas production. Furthermore, at OLR of 14.4 kg-COD/m^3/d, the COD removal was maintained as high as 87.5% in the thermophilic reactor. The conversion of influent COD to methane was maintained above 80% at all the OLR applied in both reactors. The results of this study indicated that thermophilic SDSAR is preferred for the on-site FW treatment.

1. Introduction

Food waste (FW) management is becoming more and more important because of the rapid urbanization and population growth (Curry and Pillay, 2012). Although separate collection of FW has already been a common practice in many countries, the treatment methods of FW vary according to the country's policy. In general, FW can be treated through landfill, incineration, home/centralized composting, or on-site/centralized anaerobic digestion. However, conventional landfill treatment of FW is almost no longer allowed in many countries due to shortage of landfill sites and the negative effects on the environment (Lee et al., 2013; Battistoni et al., 2007). Recently, anaerobic digestion (AD) is widely recommended as an environmentally friendly technology for FW treatment due to its energy-efficiency and biogas production as a renewable energy (Westerman and Bicudo, 2005; Zhang et al., 2007). It has been suggested as an effective way of centralized anaerobic FW treatment that FW is crushed first by food waste disposers (FWDs), and then sent to a wastewater treatment plant (WWTP) with an AD plant through sewerage systems. This could be an efficient way to avoid problems related to transportation, order and storage (Marashlian and El-Fadel, 2005). Thus, the centralized disposal/collection of FW through FWD has already been widely used in several countries such as Australia, Brazil, Canada, Japan and US (Bolzonella et al., 2003). However, centralized FW treatment based on FWD may cause an increase in organic load or toxic waste (oil and grease) load at WWTP, and corrosion risk of cement pipes related to the increased H_2S production in sewerage systems (Bernstad et al., 2013). Based on the above discussion, pretreatment of FW instead of the direct discharge into sewerage is likely to be a promising way, while on-site anaerobic treatment with FWD can become a potential method for the FW pretreatment.

Recently, most studies have focused on the co-digestion of FW and animal manure/sewage sludge (Jabeen et al., 2015; Dai et al., 2013; Zhang et al., 2013; Zhang et al., 2011), or the effect of trace metal on the fermentation performance (Facchin et al., 2013; Zhang and Jahng, 2012). Few of the studies concern on the development of an efficient anaerobic treatment technology for FWD pretreatment before the sewerage discharge (Sankai et al., 1997). Kim et al. (2015) summarized that the average moisture content of several FW including kitchen waste, mixed FW and restaurant food was 84% with 16% solids content. To verify appropriate solids

* Corresponding authors at: National Institute for Environmental Studies, Onogawa 16-2, Tsukuba 305-8506, Japan.
E-mail addresses: kobayashi.takuro@nies.go.jp (T. Kobayashi), joexu@nies.go.jp (K.-Q. Xu).

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content for a wet AD, Park et al. (2017) studied the effect of dilution with water on the performance of anaerobic FW treatment. However, based on these earlier studies, 1% of solid content in FWD-treated wastewater is at a rather low level for the wet AD. In this case, there is a need to reduce hydraulic retention time (HRT) for an efficient treatment under a proper OLR despite of the slow growth rate of anaerobic microorganisms. Temperature is considered as one of the most important factors determining the AD performance. It is widely accepted that because of its higher metabolic rates, specific growth rates and pathogens destruction rates, the thermophilic AD could improve performance and contribute to higher methane production at a high OLR condition compared with the mesophilic one (Sánchez et al., 2001; El-Mashad et al., 2004; Kim et al., 2006). However, in terms of thermodynamics, thermophilic condition is good for endergonic reactions such as acetogenesis, but not favorable to exergonic reactions such as hydrogenesis and methanogenesis (Appels et al., 2011). However, a weak point of thermophilic AD is the unstable performance in the presence of inhibitory substance. Over-load in the AD system is likely to be related to accumulation of the inhibitory substances such as volatile fatty acids (VFAs), thus causing a reduction in the biogas production. Moreover, sudden changes in OLR can often lead to an unstable digestion process (Akunna et al., 2007; Rincón et al., 2008). It is therefore very important to evaluate the effects of temperature and OLR on the on-site anaerobic treatment of FWD-treated wastewater.

The newly developed siphon-driven self-agitated anaerobic reactor (SDSAR) has already demonstrated the comparable performance in simulated FW treatment compared to the completely stirred tank reactor (CSTR) (Kobayashi and Li, 2011). Since the siphon mixing in the SDSAR can promote the dispersion of solid materials and reduce deposits without electricity consumption, it is expected to be applied to the biological waste and wastewater treatment as a cost-effective and environmentally friendly technology. However, the scum problem occurred in SDSAR under mesophilic condition treating FW from a cafeteria (Kobayashi et al., 2013). In order to evaluate the effect of operating temperature on the on-site anaerobic FW treatment, two SDSARs were run in parallel for comparison between mesophilic and thermophilic conditions. The performance of the two reactors in biogas production, organic removal, and solid removal under different HRT (hydraulic retention time) and OLRs was studied. The COD recovery from output at different OLRs was evaluated. To explore the effect of temperature and OLR on the process performance inside the SDSARs, solid distribution, pH and mixing frequency were also investigated.

2. Materials and methods

2.1. SDSAR system

A schematic diagram of the SDSAR system applied in this study is shown in Fig. 1. This reactor was made of polyvinyl chloride with an effective volume of 10 L. The temperatures of the reactor were assured by water jacket and heaters. In this study, the mesophilic and thermophilic reactor temperatures were controlled at 35 ± 1 °C and 55 ± 1 °C, respectively. The substrate was added into chamber 1, thus biogas produced in this chamber would push the liquid down until the liquid level falls to the bottom of the U-tube in the reactors. Then, the produced biogas in chamber 1 could enter chamber 2 and 3 through the U-tube rapidly. Consequently, the liquid levels in chambers 2 and 3 would decrease while the liquid level increases in chamber 1. This whole process could be considered as siphon mixing completed once in the reactor. To determine the mixing frequency, the pressure in chamber 1 was recorded by the digital pressure gauge (Krone, KDM30) once per 5 min. The FW was pumped from the substrate tank with an effective volume of 7 L. The cooling water was supplied with a cooler to the water jacket of this tank to maintain it at a temperature of around 4 °C. Sampling ports were placed in the substrate tank, on one side of the reactor body, and in the biogas collection system.

2.2. Feed stock and seed sludge

The raw and cooked FW was collected from the canteen of the National Institute of Environmental Studies, Japan. A disposal machine (Cuisinart, DLC-NXJ2PS) was used to disintegrate the raw FW. Since the assessed water use in FWD systems may vary largely from 7.2 to 19.3 L/kg FW as concluded by Bernstad et al. (2013), we follow their method which adds 12 L water to 1 kg FW for the laboratory FW grinding. To maintain a solid content of about 5% for direct methane fermentation, this crushed FW was settled in a settlement tank with an effective volume of 15 L for 24 h. Then, the settled FW was transferred and stored in the substrate tank. To prevent the trace elements deficiencies in the reactors, Fe, Co and Ni were added artificially. The trace elements concentration in the substrate was as follows: 100 mg-Fe/L, 10 mg-Co/L, and 10 mg-Ni/L, respectively (Wu et al., 2015). In this study, no extra buffer was added into the substrate. The mesophilic reactor was inoculated with sludge harvested from a full-scale mesophilic digester treating sewage sludge. The thermophilic reactor was inoculated with sludge acclimated from the mesophilic sludge over one month, according to the method described in the previous paper (Bou et al., 2005).

2.3. Operational conditions

Two SDSARs were operated for 325 (mesophilic) and 420 (thermophilic) days, respectively. At the beginning (day 1–105) of this experiment, two reactors were feed with the same FW and operated at the same HRT conditions (20 d). Then, the HRT was changed to 10 d to evaluate the effect of OLR on the reactor performance (day 106–249). Since scum problem happened at this condition in the mesophilic reactor, the HRT was then set at 15 d for two reactors during day 250–325. From day 326 to 420, only the thermophilic reactor was operated. The HRTs were maintained at 15 (day 326–357), 7.5 (day 358–395), 5 (day 396–420), respectively.

2.4. Analytical methods

The biogas production in two reactors was measured with the μFlow gas meter (Bioprocess Control AB). The biogas contents (CH_4, CO_2 and N_2) were determined by a gas chromatography (GC-8A, Shimazu). The temperatures of the injector, detector and column were set at 160 °C, 160 °C and 100 °C, respectively. The influents and effluents of both reactors were sampled for chemical oxygen demand (COD_{Cr}), pH, volatile fatty acids (VFA), TS and VS twice a week. Sludge inside the reactor was sampled and analyzed for TS and VS at least once each experimental condition from 9 sampling port on one side of the reactor and calculated the average value. TS and VS were detected according to the U.S. EPA Standard Method. The pH was measured using a pH meter (TOA-DKK) equipped with a GST-5721C probe. The samples for the analysis of VFA were centrifuged at 13,000 rpm for 8 min and filtered with 0.45 μm pore size filters as a pretreatment. The concentrations of VFA were detected by a gas chromatography (GC-2014, Shimadzu). The sample was acidified by adding 0.5 ml of 0.1 mol/L HCl solution to 0.5 ml filtrate, and then 0.1 μL mixed solution was injected to GC for analysis. COD was measured with COD digest vials (HACH). Significant differences (P-values) between mesophilic

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