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Comparison of single-stage and two-stage thermophilic anaerobic digestion of food waste: Performance, energy balance and reaction process

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ABSTRACT

The single-stage and two-stage thermophilic anaerobic digestion (TAD) in lab scale continuously stirred tank reactor systems fed semi-continuously with food waste (FW) were studied to compare their performance, energy balance and reaction processes. The experimental results showed the two TADs both had good performance at a sludge retention time (SRT) of 30 d. The VS destruction (83.22 ± 1.33%) of the single-stage TAD was comparable with the two-stage TAD (82.02 ± 1.25%) during the steady period. While the average biogas yield of the two-stage TAD (0.810 ± 0.13 L/g Added VS) was higher than that of single-stage TAD (0.775 ± 0.20 L/g Added VS) and the methane content of the former (59.1 ± 1.4%) was lower than that of the latter (61.6 ± 2.1%), the methane yields of the two TADs were similar. The single stage TAD had higher energy recovery, rate and specific rate of reaction for the four AD steps than the two-stage TAD. The two-stage TAD had to adjust its operational parameters to improve its AD efficiency.

1. Introduction

Worldwide, over 1.3 billion tonnes of foods for human consumption are wasted or lost and become food waste (FW) annually [1] from the agriculture production, during the transportation, in processing, in distribution and in consumption. That means that food loss through the food supply chain is equivalent to about one-third of the total global food production. The production of FW, which is predicted to further increase due to economic and population growth, particularly in developing countries [2], is an issue of global concern. FW is regarded as the major source of odor emanation, vermin attraction, toxic gas emission and leachate generation [3]. However, FW can be a great source of bioenergy due to its high content of organic matters with good biodegradability and inexhaustibility [4].

Anaerobic digestion (AD) is one of a number of techniques that may be used to alleviate the problems of global warming, energy security and waste management [5,6]. The AD of FW is a useful and practical process that can convert waste matters into valuable matters and energy [7]. Because of its high moisture content and high content of organic matters with good biodegradability, as well as its organic- and nutrient-rich composition, FW is considered a valuable biomass resource for biomethane recovery using AD. Unlike those traditional treatment and disposal methods of FW (such as landfills and incineration), the AD of FW, which requires less land and space, can produce renewable energy and fertilizer, reduce greenhouse gases and toxic gases such as ketones and aldehydes, and prevent pathogen proliferation [5].

AD can be performed at psychrophilic (10–20 °C), mesophilic (30–40 °C), and thermophilic (50–60 °C) temperatures to produce methane/biogas [5,8]. Although the mesophilic condition is the most commonly applied, the interest in the thermophilic condition is increasing. Among its advantages are these: higher methane yield and methane content in the biogas, lower hydrogen sulfide content in the biogas, shorter retention time, smaller reactor volume demand, and higher pathogen destruction rate and organic matter degradation rate [9]. The thermophilic AD (TAD) of FW has been recently a topic of

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interest, and some reports have appeared in the literature. For example, Menon et al. [10] optimized the micronutrient supplement for enhancing biogas production from FW in two-phase TAD and Kim [11] assessed the feasibility of TAD of FW.

As the microorganisms involved in AD can be divided into acidogenic and methanogenic ones, with different ideal environmental conditions, the AD process sometimes is designed in two stages (namely two-stage AD) to provide ideal environmental conditions for the different groups of microorganisms and allow for better process control [12]. Researchers generally accept that AD systems operated in a two-stage configuration are preferable to conventional single-stage systems in terms of methane production and digestion stability [13]. In some studies, the single-stage and two-stage AD of FW have been compared. For example, Voelklein et al. [14] compared the single-stage and two-stage AD at increased loading rates to assess the impact of an increasing loading rate on the two-stage digestion of FW, and De Gioannis et al. [15] compared the energy recovery from one- and two-stage mesophilic anaerobic digestion of FW.

Since both the thermophilic temperature and the two-stage process are regarded as having benefit to AD, it is reasonable to assume that the two-stage TAD can further enhance the performance of AD. Some studies have emerged with a focus on the two-stage TAD [16–18]. Lee et al. [16] found that the two-stage TAD with the recirculation of digester sludge could continuously produce hydrogen and methane from high-solid FW. Jariyaboon et al. [17] found that a batch two-stage TAD could be used to produce bio-hydrogen and the bio-methane potentials of skim latex serum and efficiently remove its organic content. Meanwhile some studies have compared single-stage and two-stage TAD and the results were not consistent. Leite et al. [19] found that the two-phase (namely two-stage) TAD of waste activated sludge showed clear increases in terms of organic matters removal and biogas production compared to the single stage system. However, Schievano et al. [20] found no significant differences in the overall energy recovery for the two-stage and single-stage TAD of mixture of swine manure and market biowaste and Park et al. [21] found the methane recovery ratios of single-stage and two-stage TAD of kitchen garbage were similar. Additionally, most studies about two-stage TAD and comparison of single-stage and two-stage TAD were batch or short-term ones, and continuous and long-term studies were few. Although the two-stage TAD of FW has been studied and a comparison of the single-stage and two-stage TAD has been made, few studies compared the single-stage and two-stage TAD of FW. Meanwhile, the focuses of most previous studies have been on the process performance and the microbial community, and few studies discussed the reaction processes and energy assessment.

Therefore, the objective of this study was to compare the performance, reaction processes and energy assessment of the single-stage and two-stage TAD in continuous long-term operation with FW as the substrate.

2. Materials and methods

2.1. Food waste and inoculum

The FW used as substrate in the test was synthetic FW [22]. The characteristics of this FW are summarized in Table 1. The collected FW was ground and homogenized to less than 5 mm with tap water in a blender (Waring E8000, Eberbach Co., USA) and was stored at 4 °C before feeding. Considering the commonly deficient trace elements in the FW [7,8,23,24], supplements of the cardinal elements, Fe, Co and Ni, were added: 10 mg/L of Fe ($FeCl_2·4H_2O$) and 1 mg/L of both Co ($CoCl_2·6H_2O$) and Ni ($NiCl_2·6H_2O$) [24].

The mesophilic anaerobic digested sludge from a wastewater treatment plant was acclimated over one month at 55 °C fed the used FW with an SRT of 100 d before it was used as seed sludge.

2.2. Experimental set-ups and their operation

The whole experiment apparatus comprised of a substrate tank, a single-stage TAD, and two-stage TAD (Fig. 1). The reactors for the two TADs were three lab scale continuous stirred tank reactors (CSTR). The three reactors had volumes of 2 L (T1), 8 L (T2) and 4 L (T3) with working volumes as 1.5 L (T1), 6 L (T2) and 3 L (T3), respectively. The temperature of the substrate tank was maintained at 4 °C by a cooler (CF800, Yamato Co., Japan) and a water jacket. The temperatures of the three reactors were maintained by heaters (NTT-20S, EYELA Co., Japan) and water jackets. Each AD reactor was equipped with a wet gas meter (WNK-0.5B, Shinagawa Co., Japan).

FW was semi-continuously fed to the two TADs with pumps. At the beginning, the three reactors were inoculated with 1.5 L (T1), 6 L (T2) and 3 L (T3) of the seed sludge, respectively. Subsequently, the two systems were started up by filling and drawing over a gradually shortened sludge retention time (SRT) (the hydraulic retention time is same as SRT for CSTR). The start-up period of the two systems took approximately one month and then their SRTs were stable at 30 days. The FW feeding rate was 50 mL/10 s for once and 5 times per day with the interval as 4.8 h during the steady period. The operational conditions at the SRT of 30 days for the two TADs are shown in Fig. 1. During the test, the pH of the sludge in the three reactors was not controlled or adjusted.

2.3. Analysis and calculations

Sludge samples were taken from each reactor and substrate tank twice a week to determine the total and soluble parameters. Samples for the analysis of soluble items, such as soluble COD (SCOD), total ammonia nitrogen (TAN), volatile fatty acids (VFAs) and alkalinity, were centrifuged at 8000 rpm for 15 min and filtered with 0.45 μm filters before they were analyzed. Free ammonia nitrogen (FAN) and its inhibition factor were calculated according to the method introduced by Niu et al. [25] and Zamanzadeh et al. [26]. A gas chromatograph (GC) (Shimadzu 14B), equipped with a flame ionization detector (FID) and a DB-WAXetr column, was utilized to detect VFAs and ethanol. A 0.5 mL filtrate was collected in a 1.5 mL GC vial, and 0.5 mL 0.1 mol/L HCl was also added to achieve an acidic pH. Carbohydrate, protein and lipid in the steady state were measured in the amounts used in a previous study [24]. Lactic acid (HLa) was measured according to the method outlined by Jiang et al. [27] and the pH of the digestate and substrate was measured by a pH meter (HM-30 R, DKK-TOA Co.). The biogas was sampled from each digester every day to determine its composition. The CH_4 and CO_2 contents of the biogas were detected using another GC (Shimadzu 8A) equipped with a thermal conductivity detector and a 2 m stainless steel column packed with Porapak Q. The measurements of other parameters (total solids-TS, volatile solids-VS, and chemical oxygen demand-COD) were carried out in accordance with the Standard Methods [28].

The destruction efficiencies, R_a (%), for each composition were defined by Eq. (1).

$$R_a\ (\%) = \frac{C_{a,inf.} - C_{a,eff.}}{C_{a,inf.}} \times 100 \quad (1)$$

where $C_{a,inf.}$: the concentration of composition "a" in the influent; $C_{a,eff.}$: the concentration of composition "a" in the effluent; Inf.: influent; Eff.: effluent.

2.4. Energy balance assessment

The energy assessments of the two TADs fed with FW were carried out to evaluate their scalability. To make these assessments, the scale of the TADs had to be increased. According to previous studies [29,30], the parameters for scale-up reactors were estimated from experimental