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Comparison of single-stage and temperature-phased two-stage anaerobic digestion of oily food waste

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ABSTRACT

Anaerobic digestion is an effective technology to recover energy from oily food waste. A single-stage system and temperature-phased two-stage systems with and without recycle for anaerobic digestion of oily food waste were constructed to compare the operation performances. The synchronous operation indicated the similar ability to produce methane in the three systems, with a methane yield of 0.44 L/g VS_{added}. The pH drop to less than 4.0 in the first stage of two-stage system without recycle resulted in poor hydrolysis, and methane or hydrogen was not produced in this stage. Alkalinity supplement from the second stage of two-stage system with recycle improved pH in the first stage to 5.4. Consequently, 35.3% of the particulate COD in the influent was reduced in the first stage of two-stage system with recycle according to a COD mass balance, and hydrogen was produced with a percentage of 31.7%, accordingly. Similar solids and organic matter were removed in the single-stage system and two-stage system without recycle. More lipid degradation and the conversion of long-chain fatty acids were achieved in the single-stage system. Recycling was proved to be effective in promoting the conversion of unsaturated long-chain fatty acids into saturated fatty acids in the two-stage system.

1. Introduction

Food waste (FW) is the largest fraction of municipal solid waste (MSW), accounting for about 30% [1]. Annually 20 million tons of FW, equivalent to 90 million tons of CO_2 emission, is generated in Japan [2,3]. Severe environmental pollution has been caused by the uncontrolled discharge of the FW in many countries [4,5]. Anaerobic digestion is effective in reduction and stabilization of the FW, as well as in available energy recovery, low carbon emission and limited pollution [4,6,7]. Also, commonly high in oil content Asian food leads to improved methane production [8], due to higher methane production potential for oil than other organic matter [9]. However, the low hydrolysis rate caused by high solid content in the FW poses a challenge to the conventional mesophilic digestion (MD) [10]. In addition, anaerobic digestion of oily FW may also be subjected to inhibition caused by excessive organic loading or long-chain fatty acids (LCFAs, intermediates in the anaerobic digestion of lipid) [8,11]. Thus, it is urgent to upgrade anaerobic digestion of the FW to enhance the hydrolysis and relieve the inhibition.

A thermophilic (stage I)-mesophilic (stage II) temperature-phased anaerobic digestion (TPAD) has drawn wide attention, due to the capability to improve hydrolysis and organic loading rate (OLR) [12,13]. At the hydraulic retention time (HRT) from 11 to 17 days for the treatment of sewage sludge, more than twice the volatile solids (VS) removal was achieved in the TPAD system than in the single-stage MD process [13]. Thermophilic pre-fermentation is also advantageous in the enhancement of lipid degradation, due to the improved solubility of lipid at thermophilic temperature [14]. Nevertheless, little attention has been focused on the application of the TPAD to the degradation of oily FW, let alone the conversion of lipid in the FW.

In recent years, it has been found that an effluent recycling from the stage II to stage I exerts considerable influence on the overall performance of the TPAD, and makes a hydrogen–methane two-stage process possible [15,16]. A TPAD process with recycle (TPAD-R) was operated with stage I at the HRT of 1.3 days (OLR 38.4 g VS/L/d) and stage II at the HRT of 5.0 days (OLR 6.6 g VS/L/d), resulting in the hydrogen yield of 205 mL/g VS_{added} and

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methane yield of 464 mL/g VS_{added} [15]. Unfortunately, the previous studies about the TPAD with recycle (TPAD-R) focus on the process feasibility, and few investigations have been carried out on the synchronous comparison of the differences between the TPAD-R and the MD. In addition, biomass recycling favors prevention of the inhibition caused by LCFAs and the preservation of acclimated biomass with greater lipid degradation capabilities [17,18]. However, in the previous investigation into the TPAD-R process, little attention was paid to the conversion of oily fraction in the FW.

TPAD and TPAD-R were constructed in this study to treat oily FW, with MD as the control test. A comparison of the synchronous operation results allows the operation performance to be evaluated in terms of the possibility to upgrade the mesophilic digestion of oily FW with TPAD, and highlights the effects of a recycle system on the TPAD of the FW. In addition, analyses of the conversion of lipid were conducted to evaluate the degradation characteristics in the MD, TPAD and TPAD-R.

2. Materials and methods

2.1. Feedstock and seed sludge

Raw FW was fetched from the dining hall at the National Institute of Environmental Studies, Japan. Thereafter, the raw FW was diluted 2.4 folds in a tank equipped with a stirrer. A shear pump was used to shear the diluted FW to less than 5 mm. The characteristics of the prepared FW can be found in Table 1. Considering the commonly deficient trace elements in the FW [19–22], cardinal elements, Fe, Co and Ni, were supplemented, with Fe ($FeCl_2{\cdot}4H_2O$) of 100 mg/L, Co ($CoCl_2{\cdot}6H_2O$) of 10 mg/L and Ni ($NiCl_2{\cdot}6H_2O$) of 10 mg/L, respectively [23]. The mesophilic seed sludge was from the mesophilic digester in a wastewater treatment plant for sewage sludge treatment. The thermophilic seed sludge was acclimated from the mesophilic sludge over one month, with reference to the previous method [24].

2.2. Experimental set up and operation

The whole experiment apparatuses were comprised of a substrate tank, a single-stage MD system, and two-stage systems TPAD and TPAD-R. The schematic diagram is illustrated in Fig. 1. The volume of stage II in the two-stage systems were designed as 4 times the volume of stage I, with reference to the previous studies [25,26]. The effluent from stage II of the TPAD-R was recycled to stage I with the same flow rate as the influent of the whole system [23,27,28]. The temperature of the tank was maintained at 4 °C by a cooler and a waster jacket. The temperatures of the reactors were assured by water jacket and heaters. Each reactor had its own gas measuring unit (wet gas meter WNK-0.5, Shinagawa Corporation, Japan).

The MD and stage II of two-stage systems were seeded initially with mesophilic digested sludge. Stage I of the two-stage systems were seeded with thermophilic digested sludge. At the beginning, the seed sludge was transferred into the corresponding reactors until the working volume of each reactor was established. Subsequently, the systems were started up by feeding and withdrawal over a gradually shortened HRT, from 100 days to 50 days, and then to 30 days. The operation at the HRTs of 100 days and 50 days took approximately one month. The operation at the HRT of 30 days was maintained more than two hydraulic turnovers. The operational conditions at the HRT of 30 days are shown in Table 2.

Table 1
Characteristics of FW used in this study.

Items	Unit	Values
pH		3.65 ± 0.06
TS	%	7.62 ± 0.29
VS	%	7.21 ± 0.29
T-COD	g/L	101.2 ± 6.1
SCOD	g/L	33.7 ± 1.5
T-carbohydrate	g/L	31.0 ± 5.4
S-carbohydrate	g/L	4.1 ± 0.3
T-protein	g/L	14.1 ± 1.9
S-protein	g/L	1.6 ± 0.1
T-lipid	g/L	13.9 ± 2.2
S-lipid	g/L	0.3 ± 0.0
VFA	mgHAc[a]/L	2074 ± 207
NH_4^+-N	mg/L	203 ± 15

[a] The concentrations of all individual VFA were calculated as acetic acid.

2.3. Sampling and analytical methods

The volume of biogas was noted on a daily basis. A 0.5 mL of biogas was taken from the gas pipelines, and injected to a gas chromatography (GC-8A, Shimazu Corporation, Japan) equipped with a thermal conductivity detector and a stainless steel column packed with Shincarbon ST (Shimadzu GLC) to measure the relative composition of hydrogen, nitrogen, methane and carbon dioxide. The temperatures of the injector, detector and column were set 160 °C, 160 °C and 100 °C, respectively.

Samples, including substrate, were taken from the sampling ports of each reactor or substrate tank twice a week to determine pH, total solids (TS), VS, chemical oxygen demand (COD), and LCFAs. Samples for the analysis of soluble items, such as, soluble COD (SCOD), NH_4^+-N, volatile fatty acids (VFAs) and alkalinity, were centrifuged at 13,000 rpm for 5 min and filtered using filters with 0.45 μm pore size before they were analyzed. Data in the steady state, relatively constant VS reduction (5%), were collected at least three times. COD was determined by COD Digest Vials (HACH). NH_4^+-N were analyzed using the automatic nutrient analyzer (TrAACs 2000-autoanalyzer system, Bran + Luebbe). A gas chromatography (GC14B, Shimadzu), equipped with a flame ionization detector (FID) and a DB-WAXetr column, was utilized to detect VFAs. A 0.75 mL filtrate was collected in a 1.5 mL GC vial, and 0.75 mL 0.1 mol/L HCl solution was also added to achieve an acidic pH. The sample injection volume was 1.0 μL. LCFAs were measured as fatty acids methyl esters using a gas chromatograph (6890 series GC system, Agilent) with a FID. DB-WAX capillary column (Agilent J&W) was used for separation. Carbohydrate, protein and lipid in the steady state, were measured according to the previous reports [29]. Measurement of the other items followed Standard Methods [30].

2.4. Calculations

The removal rates for each item, the ratios of hydrolysis, acidogenesis and methanogenesis and the energy balance were calculated by the methods reported by Wu et al. [29].

3. Results and discussion

3.1. Process performance

The time courses of pH, biogas production rate, biogas composition, TS and VS, VFA and NH_4^+-N in the MD, TPAD and TPAD-R are shown in Fig. 2. The average values in the steady state are presented in Table 3. The pH in the effluent of each system was maintained above 7.0, and VFAs were not detected in the steady state. It suggested the stabilization of operation in the MD, TPAD and