Fuel 169 (2016) 7–14

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Upgrading of mesophilic anaerobic digestion of waste activated sludge by thermophilic pre-fermentation and recycle: Process performance and microbial community analysis

Li-Jie Wu [a], Atsushi Higashimori [a], Yu Qin [a], Toshimasa Hojo [a], Kengo Kubota [a], Yu-You Li [a,b,*]

[a] Department of Civil and Environmental Engineering, Graduate School of Engineering, Tohoku University, Aoba 6-6-06, Aramakiaza, Aoba-ku, Sendai 980-8579, Japan
[b] Department of Frontier Science for Advanced Environment, Graduate School of Environmental Studies, Tohoku University, Aoba 6-6-20, Aramakiaza, Aoba-ku, Sendai 980-8579, Japan

ARTICLE INFO

Article history:
Received 21 September 2015
Received in revised form 24 November 2015
Accepted 30 November 2015
Available online 11 December 2015

Keywords:
Waste activated sludge (WAS)
Temperature-phased anaerobic digestion (TPAD)
Two-stage
Recycle
Methane

ABSTRACT

In order to upgrade the conventional mesophilic anaerobic (MD) of waste activated sludge (WAS), a thermophilic pre-fermentation and a recycle system were introduced to form continuous thermophilic–mesophilic temperature-phased anaerobic digestion (TPAD) and TPAD with recycling capability (TPAD-R). The synchronous operation, with the MD as control, indicated significant improvements in reduction of solids and the ability to produce methane in the TPAD and TPAD-R, with a similar amount of improvement in both systems. VS reduction was improved from about 40% in the MD to 50%, and the methane recovery rates were improved from 0.53 L/g VS destroyed in the MD to 0.63 L/g VS destroyed accordingly. The thermophilic stage in the TPAD and TPAD-R made a large contribution to organic matter degradation and solubilization, and the specific hydrolysis rate in thermophilic stage attained 0.2 gCOD/g VS/d. Furthermore, under experimental conditions, the thermophilic stage in the TPAD and TPAD-R also played an important role in acidogenesis and methanogenesis. The thermophilic pre-fermentation made *Firmicutes* and *Methanosarcina* become the main phylum and genus in the mesophilic stage, accounting for 44% and 54%, respectively. The recycle system improved the diversity of bacteria and archaea in the thermophilic stage of the TPAD-R. The TPAD and TPAD-R also achieved about twice the net energy of the MD.

1. Introduction

The disposal of sewage sludge is a problem of growing importance, representing up to 50% of the current operating costs of a wastewater treatment plant (WWTP) [1]. Anaerobic digestion has been employed extensively in WWTPs to stabilize primary and activated sludge for decades. However, the process performances are limited with a mean conversion of organic matter from 30% to 50% [2]. Waste activated sludge (WAS) is characteristic of a lower biodegradability than primary sludge [3], due to the protection of microbial cell walls on intracellular organics [4]. In addition, over the past decades, in order to meet reduced nitrogen discharge limits, process adaptations in WWTPs, including the removal of primary settlings and primary sludge streams and increased retention times for biological nutrient removal processes, resulted in greater volumes of WAS, and more difficult degradation [5,6]. Therefore, there is an urgent need for developing an innovative approach to anaerobic digestion of WAS. The hydrolysis of large organic molecules in sludge is the rate-limiting step to achieve rapid degradation [7,8]. Therefore, the critical issue to upgrade the conventional digestion of WAS is to enhance the hydrolysis of WAS [9,10].

Temperature-phased anaerobic digestion (TPAD), with thermophilic digestion as pre-fermentation of mesophilic digestion (MD), can combine the advantages of thermophilic and mesophilic digestion and optimize the process due to staging [11,12]. It has been proved that thermophilic–mesophilic process was an effective treatment for increasing methane production and volatile solids (VS) destruction, compared with a single-stage mesophilic digestion, with a relatively low energy input and capital cost [13,14]. Also, it is possible to operate TPAD system at higher loadings [14,15]. Unfortunately, in the previous investigations into the TPAD process, little attention was paid to the upgrading of anaerobic digestion of WAS, let alone the analyses of the microbial community.

* Corresponding author at: Tohoku University, Aoba 6-6-06, Aramakiaza, Aoba-ku, Sendai 980-8579, Japan. Tel.: +81 22 795 7464; fax: +81 22 795 7465.
E-mail address: gyokuyu.ri.a5@tohoku.ac.jp (Y.-Y. Li).

http://dx.doi.org/10.1016/j.fuel.2015.11.091
0016-2361/

Nomenclature

WWTP	wastewater treatment plant	VFA	volatile fatty acid
WAS	waste activated sludge	PCOD	particulate COD
HRT	hydraulic retention time	MD	conventional mesophilic anaerobic digestion
TS	total solids	TPAD	temperature-phased anaerobic digestion
VS	volatile solids	TPAD-R	temperature-phased anaerobic digestion with recycle

In recent years, on the basis of anaerobic staging, recycling from the end stage to the front stage has been introduced to optimize the process of the two-stage system [16–18]. Li et al. applied the TPAD with recycle (TPAD-R) to the treatment of high solid waste, and demonstrated the process feasibility [19–21]. Few investigations have been carried out on the upgrading of anaerobic digestion of WAS by TPAD-R. In addition, the quantitative advantages of TPAD-R have not been detailed, and no comparative evaluation of TPAD with and without recycling has been made.

Thermophilic–mesophilic TPAD and TPAD-R were constructed in this study to treat WAS, with MD as the control test. A comparison of the synchronous operation results allows the evaluation for each system in terms of the feasibility with TPAD and TPAD-R upgrading MD of WAS, and highlights the differences between TPAD and TPAD-R. In addition, the microbial community analysis in each reactor was conducted to evaluate and validate the process effects.

2. Materials and methods

2.1. Substrate and seed sludge

The substrate fed to the experiment reactor was concentrated WAS, obtained from Senen purification centre, Tagajo, Miyagi, Japan. The characteristics of the WAS in the steady state are shown in Table 1. The mesophilic seed sludge was from the mesophilic digesters in a WWTP for sewage sludge treatment. The thermophilic seed sludge was obtained from a thermophilic anaerobic digester treating human waste and septic tank sludge.

2.2. System construction and operation

Three laboratory-scale anaerobic digestion systems, two-stage systems TPAD and TPAD-R and a single-stage system MD were constructed. The schematic diagram of the constructed systems is illustrated in Fig. 1. One substrate tank was set to supply the feed stock for each system. The temperature of the feeding tank was controlled at 4 °C by the water jacket and a cooler. Each two-stage systems contained two reactors, stage I and stage II. The temperatures of the reactors for every system were assured by water jacket and heaters. Wet gas meters (WNK-0.5, Shinagawa Corporation, Japan) were assembled in each reactor to measure the gas production volumes. The reactor was fed and withdrawn semi-continuously 6–12 times per day by a peristaltic pump.

The MD and stage II of the 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 hydraulic retention time (HRT) from 100 days to 50 days, and then to 30 days. The experimental parameters and conditions in HRT 30 days are shown in Table 2.

2.3. Sampling and analytical methods

A steady state, defined as relatively constant VS reduction (5%), was attained after at least two hydraulic turnovers. Samples, including substrate, were taken from the sampling ports of each reactors or substrate tank every three or four days. The volume of biogas was noted on a daily basis. Measurement of pH, total solids (TS), VS, COD, and NH_4^+–N followed Standard Methods [22].

The examination methods for gas composition, organic matter including carbohydrate, protein and lipid, and volatile fatty acid (VFA) components referred to the previous report [23].

Data in the steady state were collected at least three times. The average values of these measurements are presented in Table 1. In

Table 1
Average of the experiment results in the steady state.

	Items		Unit	WAS	MD	TPAD		TPAD-R	
						I	II	I	II
Digested sludge	pH			5.82 ± 0.05	7.34 ± 0.03	7.54 ± 0.05	7.53 ± 0.05	7.65 ± 0.05	7.58 ± 0.03
	TS		%	4.62 ± 0.07	3.02 ± 0.07	3.38 ± 0.05	2.77 ± 0.06	3.08 ± 0.04	2.75 ± 0.06
	VS		%	3.62 ± 0.06	2.14 ± 0.07	2.33 ± 0.04	1.84 ± 0.04	2.09 ± 0.06	1.82 ± 0.04
	T-COD[a]		g/L	58.5 ± 0.2	32.0 ± 1.0	36.7 ± 1.1	27.4 ± 0.8	31.5 ± 1.2	27.0 ± 0.8
	SCOD		g/L	8.7 ± 1.6	4.9 ± 0.3	13.8 ± 0.7	6.4 ± 0.2	10.4 ± 0.2	6.7 ± 0.3
	T-Carbohydrate		g/L	6.5 ± 0.4	4.0 ± 0.2	4.9 ± 0.1	3.5 ± 0.2	4.3 ± 0.1	3.6 ± 0.1
	S-Carbohydrate[b]		g/L	0.8 ± 0.1	0.7 ± 0.0	1.7 ± 0.1	0.9 ± 0.1	1.4 ± 0.1	0.9 ± 0.0
	T-Protein		g/L	20.4 ± 1.1	11.0 ± 1.3	9.9 ± 0.7	8.9 ± 0.2	10.0 ± 0.5	8.8 ± 0.4
	S-Protein		g/L	1.7 ± 0.3	1.5 ± 0.1	3.0 ± 0.2	1.7 ± 0.0	2.3 ± 0.1	1.7 ± 0.0
	T-Lipid		g/L	4.7 ± 0.3	3.5 ± 0.4	3.7 ± 0.4	3.6 ± 0.2	3.8 ± 0.1	3.6 ± 0.3
	S-Lipid		g/L	2.3 ± 0.3	2.2 ± 0.1	2.7 ± 0.2	2.1 ± 0.1	2.3 ± 0.2	2.3 ± 0.1
	VFA		mg HAc/L[c]	920 ± 160	N.D.	N.D.	N.D.	210 ± 10	N.D.
	NH_4^+–N		mg/L	550 ± 40	2140 ± 80	2250 ± 60	2770 ± 40	2470 ± 60	2770 ± 50
Biogas	Production rate		L/L/d		0.41 ± 0.01	2.18 ± 0.05	0.22 ± 0.01	2.03 ± 0.05	0.23 ± 0.01
	Composition	CH_4	%		63.4 ± 0.4	60.9 ± 0.3	66.6 ± 0.2	59.9 ± 0.4	69.8 ± 0.2
		CO_2	%		35.3 ± 0.5	38.5 ± 0.3	32.4 ± 0.1	39.5 ± 0.4	29.4 ± 0.3

[a] 'T' refers to 'Total'.
[b] 'S' refers to 'Soluble'.
[c] All individual VFA were calculated as acetic acid.