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Effect of two-step thermo-disintegration on the enhancing solubilization and anaerobic biodegradability of excess waste sludge

Ik-Jae Lee [a], Young-Shin Lee [b], Gee-Bong Han [c,*]

[a] Department of Technology Development, Mirae G&C Ltd., E-dong #806 Haan-ro 60, Kwangmyung-si, Kyunggi-do, Republic of Korea
[b] Department of Environment Engineering, Hanseo University, Seosan 356-706, Chungcheongnam-do, Republic of Korea
[c] Department of Biosciences & Environmental Engineering, The Catholic University of Korea, 43 Jibong-ro, Bucheon-si, Kyunggi-do, Republic of Korea

HIGHLIGHTS

- The solubilization of EWS with an innovative TSTS-sys system was evaluated.
- The effect of two-step thermo disintegration on the CH_4 production was tested.
- The two-step thermo disintegration with TSTS-sys system enhanced 71% of average CH_4 rate.
- The plateau of solubilization and CH_4 production rate was showed at 180 °C.

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ABSTRACT

The effectiveness of the pretreatment with a novel two-step thermo-solubilization system (TSTS-sys) on the disintegration of excess waste sludge (EWS), as well as the biogas (CH_4) production efficiency of the following anaerobic mesophilic digestion, was experimentally evaluated. Carbohydrate was solubilized higher than proteins, and the concentration of VFAs increased also after pretreatment with TSTS-sys. CH_4 was produced in the rate of 322 mL CH_4 g^{-1} VS $_{feed}$ from the pre-treated EWS at 180 °C for 60 min operation. The CH_4 composition ratios in the produced biogas were averaging 55.3 ± 076, 62.8 ± 097 and 71.2 ± 1.03% for control 1, 2 and the second step of TSTS-sys, respectively. The CH_4 production rate of pre-treated EWS with the two step thermal solubilization of TSTS-sys was enhanced by 63.9% and 19.5% higher compared to the control 1 and 2, respectively. The additionally enhanced biogas production rate was still insufficient to cover the energy balance deficit caused by the pre-treatment. In this study, two-step thermal solubilization of TSTS-sys showed to be an efficient feasible pretreatment for enhancing the disintegration of EWS.

1. Introduction

Waste activated sludge is generated during the process of wastewater treatment and the cost for excess microbial waste sludge disposal is becoming an economic burden due to associating with 50–60% of the total operating costs of wastewater treatment plants [1,2]. With regards on the alleviation of operating cost, allowing reduction of sludge volume and mass is essential to select the best available strategy. Anaerobic sludge digestion is the most well known method for excess waste activated sludge treatment with regards on sludge volume reduction and production of energy-rich biogas. Thus, anaerobic sludge digestion received an increasing attention and includes the reduction of sludge volume and the organic matter stabilization [3,4].

Accordingly, anaerobic excess sludge digestion can be a sustainable alternative for solid wastes treatment for disposal. However, glycan strands contained in the microbial cell walls as constituents of excess waste sludge hinder cell wall degradation, and thus the excess waste sludge hydrolysis often causes lowering overall sludge digestion efficiency (20–50%) [5]. On the other hand, intracellular organic materials of the microbial cells are readily released through disintegrating cell walls by thermal, chemical and mechanical pretreatment. Therefore, limiting factor for anaerobic excess waste sludge digestion could be its slow reaction rate for hydrolysis [6], and thus various methods as pretreatment have been attempted to enhance sludge digestion efficiency [1].

* Corresponding author at: Department of Biosciences & Environmental Engineering, The Catholic University of Korea, San 43-1 Yeokgok-dong, Wonmi-gu, Bucheon, Kyunggi-do, Republic of Korea.

E-mail address: geebhan@catholic.ac.kr (G.-B. Han).

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Most of these pretreatment methods adopt disintegrating or solubilizing complicated particulate matter of microbial excess waste sludge. Among these methods, thermal decomposition induces hydrolysis of excess waste sludge flocs by microbial cell lysis and disrupting the gel structure. Due to the reactive mechanisms occurring during thermal process, physico-chemical characteristics of microbial excess waste sludge are substantially affected through cell lysis and solubilization [7,8]. Effects of numerous temperatures on the sludge pretreatment were evaluated at various conditions of 60–270 °C [9]. Once the organics of microbial cells are solubilized, the microbial sludge turns into more convenient state for further treatment. Thermal hydrolysis of microbial excess waste sludge is a well-known treatment method destructing pathogens for the agricultural utilization of stabilized microbial excess waste sludge. Thermal method among pretreatments appeared to be more efficient with regards on solubilizing excess waste sludge [8]. The process of excess waste sludge solubilization is operated at the temperature range of 120–210 °C and operating times of 30–60 min. In the literature, the deterioration of biological sludge degradability was also reported due to the production of recalcitrant soluble organic matters and inhibitory intermediates by thermal hydrolytic pretreatment at the temperature higher than 180 °C [10]. Thus, melanoidins as refractory constituents are produced by Maillard like reactions due to molecular structure modifications [11]. Pressure is required to be in the range of 600–2500 kPa at these temperatures [12].

The purpose of microbial excess waste sludge solubilization by thermal pretreatment is to enhance anaerobic digestion performance [8]. Anaerobic sludge digestion attracts an increased attention and enables the stabilization of organic constituents, pathogens destruction and the sludge volume reduction [3,4]. Anaerobic sludge digestion is consisted of several phases of hydrolysis, acidogenesis, and methanogenesis. The hydrolysis rate often limits the efficiency of anaerobic sludge digestion, and thus thermal sludge solubilization was developed to raise the stabilization rate and to enhance the anaerobic sludge digestion performance. However, in spite of the advantages relevant to the performances and effects of thermal pretreatment on physico-chemical properties of microbial excess waste sludge and its implementation, more effective thermal pretreatment concerning its consequences on microbial excess waste sludge solubilization is necessary to overcome the currently encountering limitations such as the deterioration of biological sludge degradability due to the production of recalcitrant soluble organic matters and inhibitory intermediates by thermal hydrolytic pretreatment. Therefore, to evaluate the new innovative two-step thermo-solubilization system (TSTS-sys) and provide a comprehensive insight into solubilization of microbial excess waste sludge under the condition of a 180 °C pressurized thermal pretreatment, the potential effects of the TSTS-sys on anaerobic microbial sludge digestion was investigated.

In this work, the mutual effects on the performance of the TSTS-sys were examined with a comprehensive assessment on the conditions for increasing solubilization rate and anaerobic sludge digestion efficiency at numerous pretreatment conditions. Solubilization rates at different pretreatment conditions were tested, and biodegradability test for biochemical methane potential was conducted using the whole part and the soluble fraction of pretreated sludge. The microbial excess waste sludge was solubilized to ascertain the major constituent producing methane and attain a highly efficient pretreatment effect. The specific objectives for this study are to evaluate the effect of thermal solubilization pretreatment on the enhancement of the anaerobic excess waste sludge digestion. The influence of various pretreatment conditions was assessed with TSTS-sys regards on the effectiveness of (1) excess waste activated sludge solubilization, (2) particulate matters reduction, and (3) biogas production.

2. Materials and methods

2.1. Sludge characteristics

The excess waste sludge (EWS) was sampled from a municipal sewage treatment plant in Bucheon-si Kyunggi-do, Korea. The EWS samples were continuously homogenized and stored at 4 °C until using for the feedstock of the test. The EWS was initially pretreated to obtain homogenized samples sufficient for the solubilization with a liquefaction system mechanical tool (TSTS-sys). Table 1 shows the main characteristics of the EWS used in this test and triplicate samples for analysis were measured whenever necessary.

To examine solubilization rate of liquid organic constituents, glucose and albumin were selected for carbohydrate and protein analyses, respectively. The initial characterization of the EWS sample showed the pH value 7.14, which causes no disturbing effects on the anaerobic digestion. Average TS and VS content of the EWS during initial characterization period were about 11.3 g L^{-1} and 7.9 g L^{-1}, respectively. Volatile fatty acids (VFAs) concentration was 0.876 g L^{-1}, which is adequate for the initial operation of anaerobic digestion.

2.2. Operation of the two-step thermo-solubilization (TSTS-sys) and whole system

The thermal pretreatment of the EWS was carried out using the new innovative two-step thermo-solubilization system (TSTS-sys), which was designed to conduct solubilization of the EWS through two-step process. The first step is to be conducted by liquefaction reactor consisting of curved pipe (STS 316, L: 18.5 m, ø: 17.5 mm) containing sample volume of 4.5 L. The second step is to be conducted by molecular structure disintegrating reactor consisting of tubular pipe (STS 316, L: 1.6 m, ø: 84.9 mm) containing sample volume of 9.0 L. Both reactors of the TSTS-sys were regulated by a proportional integral derivative (PID) controlling system. At the end of the first step, the reactor content was depressurized immediately into the second step reactor. The progressing cavity pump (MONO pump) was used to feed and provide the required pressure (2000 kPa) into the TSTS-sys. Pressure control was regulated with electric ball valve at the end of liquefaction reactor in the first step of TSTS-sys. The TSTS-sys is designed to enhance the biodegradability of intracellular materials and particulate polymeric constituents of the EWS by two-step thermo-solubilization. The TSTS-sys is also operated to avoid the production of melanoidins as refractory constituents by Maillard like reactions and enhance CH_4 production rate of pre-treated EWS with the two step thermal solubilization. Fig. 1 shows the schematic process diagram of the whole proposed system including the TSTS-sys.

The whole process illustrated in the Fig. 1 is consisted of 3 groups such as TSTS-sys, cooling system with feeding reservoir for solubilized liquor, and anaerobic digester (STS 304, 15 L). The operating conditions of temperature and pressure for the TSTS-

Table 1
The excess waste sludge characteristics.

Parameters	Unit	Average
pH		7.14 ± 0.1
TS	g L^{-1}	11.3 ± 0.52
VS	g L^{-1}	7.90 ± 0.39
COD	g L^{-1}	10.4 ± 0.49
SCOD	mg L^{-1}	670 ± 46
VFA	mg L^{-1}	876 ± 57
NH_4^+-N	mg L^{-1}	215 ± 16
Alkalinity	mg L^{-1} as $CaCO_3$	202 ± 15