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Acidic thermal post-treatment for enhancing anaerobic digestion of sewage sludge

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ABSTRACT

Acidic thermal post-treatment (ATPT) was examined for treatment conditions in a batch study, and was demonstrated to enhance anaerobic digestion of sewage sludge in a continuous study. In the batch study where anaerobically digested sludge was the substrate in view of a post-treatment mode, higher ATPT temperatures between 25 and 180 °C improved volatile suspended solids (VSS) destruction and methane production, but generated color significantly at 180 °C. Lower ATPT pH between 2 and 6 enhanced sludge dewaterability (as capillary suction time), and slightly suppressed color generation. In the continuous study, two single-stage anaerobic digestion processes were operated at 35 °C and 20 days hydraulic retention time. For one of the processes, ATPT at 170 °C and pH 5–6 for 1 h was incorporated in the recycle line. Approximately 75% of VSS destruction was achieved in the ATPT process, which was 2–2.5 times more than that in the control process, 30–37%. The ATPT process also showed 14–21% more methane production and 22–23% better dewaterability, but formed around three times more color, compared to the control process. Sulfuric acid as the acidifying agent caused more release of phosphate from the digested sludge, which enables efficient phosphorus recovery.

Introduction

Anaerobic digestion is suited for treating organic waste with high water contents, such as industrial wastewater, sewage sludge, and municipal and agricultural solid waste. It enables the decomposition of organic matter as well as the production of fuel gas, methane. Furthermore, many other valuable materials can be produced or recovered through anaerobic digestion, including hydrogen, volatile acids and phosphorus. In light of these facts, anaerobic digestion has been recognized as one of the core technologies for recycling energy and materials from waste, and contributing to sustainable developments.

In the case of sewage sludge, however, the organic fraction converted into biogas by the current anaerobic digestion technology is not high enough, while the production of sewage sludge is explosively increasing worldwide. Waste activated sludge has been particularly paid attention to, because of its more recalcitrant nature to anaerobic biodegradation than primary sludge. A classic method to overcome the difficulty is the application of mechanical, thermal, chemical, biological or other pre-treatment methods to anaerobic digestion. Several literature reviews on this topic have been published in recent years, indicating the world's technological, environmental and economical requirements for sludge minimization and biogas maximization [1–5].

So far, the major pre-treatment methods reported to be employed in full-scale installations have been thermal hydrolysis, enzyme hydrolysis and ultrasound, and in particular, the Cambi and BioTHELYS processes that combine thermal hydrolysis with mechanical dehydration of influent sludge, have been most widely applied in the world [6]. Thermal pre-treatment of sewage sludge has been demonstrated to enhance not only sludge dewaterability but also anaerobic digestibility [1–5]. Most of the previous studies report optimal temperatures of 160–180 °C and treatment durations of 30–60 min, although the latter appears to have a secondary effect [4]. Drawbacks are associated with the generation of hardly degradable chemical oxygen demand (COD), including colored compounds, and possibly increased fine suspended solids (SS) [2,4].

A recent study conducted by the authors implicated that the thermal treatment at acidic pH is preferable, particularly from the point of view of the enhanced dewaterability of digested sludge and the mitigation of color generation [7]. Alkaline conditions are generally more compatible with anaerobic digestion due to the increase of alkalinity than acidic conditions [3], and therefore have been favored as pre-treatment in the previous investigations. However, Devlin et al. [8] recently reported that acid pre-treatment can speed up the hydrolysis of waste activated sludge, increase methane yield and reduce cationic polymer addition for dewatering.

On the other hand, there is another aspect to be taken into consideration, when applying any treatment method, that is, process

Abbreviations: ATPT, acidic thermal post-treatment; COD, chemical oxygen demand; CST, capillary suction time; HRT, hydraulic retention time; PO_4-P, phosphate phosphorus; SS, suspended solids; T-P, total phosphorus; TS, total solids; VS, volatile solids; VSS, volatile suspended solids.

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configuration. One of the authors has examined some process configurations for mesophilic anaerobic digestion of sewage sludge, when incorporated with thermal treatment of 120 °C and for 1 h [9]. The post- and interstage-treatment configurations were superior in terms of organic matter destruction and methane production (here, the post-treatment configuration refers to a single-stage process with the thermal treatment of recycled digested sludge, and the interstage-treatment configuration a two-stage process with the thermal treatment placed between the first and second stage). The author concluded that the thermal treatment as pre-treatment tends to act on degradable parts of sewage sludge, and that it is more effective on anaerobic digestibility to apply the thermal treatment after sewage sludge is digested once. This is further supported by the recent two papers on the interstage-treatment, one with mixed sludge [10] and another with waste activated sludge [11].

Considering the energy-conservative nature of heat, another advantage of the thermal post-treatment configuration is that the heat spent for it can be reused for the digester heating. In addition, the digester operation will be more economical when thickening the digested sludge recycled, because the volume reduction can save heating energy and thus costs for the thermal post-treatment.

This research focused on acidic thermal treatment and its application to anaerobic digestion of sewage sludge as the post-treatment configuration. Firstly, treatment conditions of acidic thermal post-treatment (ATPT) were examined in a batch anaerobic study, as investigation of the thermal treatment at acidic pH has not been done in detail. Secondly, the effectiveness of ATPT was demonstrated in a continuous experiment. Centrifugation was applied for solids separation to add acidic thermal treatment to digested sludge in the recycle line.

Methods

Batch study

The temperature and pH conditions of ATPT were examined by a batch test employing 120 mL serum bottles. Anaerobically digested sludge was used as the substrate, in particular, to observe the effects on the anaerobically refractory part of sewage sludge. The digested sludge was taken from a municipal anaerobic digester in Fukui City, Japan, and also served as the seed sludge.

The acidic thermal treatment was performed with a stainless steel autoclave, which had a total volume of 2.5 L and a maximum pressure of 1.5 MPa (TZA100-15K-LG, Unicontrols, Tokyo, Japan). The temperature and initial pH of acidic thermal treatment were varied at three levels each; 25, 100 and 180 °C for temperature, and 2, 4 and 6 for pH with hydrochloric acid. The treatment duration of 1 h and mixing speed of 300 rpm were fixed. The headspace was air, meaning there was no substitution with other gases.

25 mL each of the substrate and seed sludge was adjusted to the pH of 7.0–7.3, and placed in the serum bottles. Then, the bottles were filled with a mixture of 80% N_2 and 20% CO_2, sealed with rubber caps and aluminum stoppers, and incubated in a water bath (MMS-1, Eyela, Tokyo, Japan) at 35 °C and 40 strokes/min. Duplicated bottles were used for each condition. For 20 days, the volume of methane gas produced was measured in appropriate time intervals by means of gas analysis with a gas chromatograph and subsequent water replacement in a 100 mL graduated cylinder [12]. The cylinder contained an acidic salt solution to minimize the absorption of carbon dioxide. Also, the solids concentrations, capillary suction time (CST) and color were analyzed before and after the batch test.

Continuous study

As drawn in Fig. 1, two single-stage anaerobic digestion processes were prepared: the control process, and the process combined with ATPT in the recycling line, called ATPT process hereafter. The hydraulic retention time (HRT) was equally set at 20 days based on the flow rate of influent sewage sludge. In the ATPT process, the solids in the digested sludge were separated by centrifugation (2000 rpm for 10 min; LCO6-SP, Tomy Seiko, Tokyo, Japan), stored at 4 °C, and received ATPT once a week. Then, the thermally treated sludge was recycled to the digester at the recycle ratio of 30%. This reduced the actual HRT of the digester to 15.4 days, because the biomass in the recycled digested sludge is killed and converted into substrate by the ATPT. The employed flow rates and sampling volumes are also summarized in Fig. 1.

Erlenmeyer flasks with the effective volume of 2.0 L were used as the anaerobic digesters. The flasks had a rubber stopper with two glass ports, each for the inlet/outlet of sludge or for the outlet of gas. These digesters were placed in a constant temperature room maintained at about 35 °C, and were operated in a daily draw and fill mode at the rotating speed of 100 rpm. The biogas produced was collected in an aluminum-coated gas bag (CCK, GL Science, Tokyo, Japan), and then quantified with a wet gas meter (WS-1A, Sinagawa, Tokyo, Japan).

The autoclave mentioned above was also used for the ATPT in this continuous study. Based on the results of the batch study, the ATPT conditions of 170 °C and pH 5–6 were employed, as will be described later. The duration and mixing speed were identical to those for the batch study. Hydrochloric acid was used to decrease the pH in Run 1, and sulfuric acid in Run 2. During the thermal treatment, charcoal-like materials were often produced and adhered to the inner surface of the autoclave. Larger particles of them were removed from the recycled sludge to minimize adverse effects on the digester operation.

The substrate was gravitationally thickened sewage sludge taken from a municipal combined wastewater treatment plant located in Fukui City, Japan. It had TS of about 2.5%, and stored in a refrigerator at 4 °C. For feeding, the substrate was warmed up to >30 °C to prevent temperature shocks to the digesters. The seed sludge was obtained from lab-scale digesters, which were operated in a similar fashion. The characteristics of the seed sludge were TS of 35.0 g/L, VS of 17.9 g/L and the VS/TS ratio of 0.51. TS, VS, suspended solids (SS), volatile suspended solids (VSS), total and soluble COD, total phosphorus (T-P), phosphate phosphorus (PO_4-P), CST, color, pH and the volume and constituents of biogas were analyzed once a week.

Analytical procedures

Most of the analyses were performed in accordance with Standard Methods [13]. The soluble fraction of sludge samples was prepared through centrifugation (15,000 rpm and 10 min; CF15R, Hitachi, Tokyo, Japan) and membrane filtration (0.45 μm cellulose-ester; A045A047A, Advantec, Tokyo, Japan). The closed reflux colorimetric method (Standard Methods 5220D) was employed for COD using a spectrophotometer DR/4000U (Hach, Colorado, USA). The dewaterability of sludge was investigated by the CST (Standard Methods 2710G) using a CST meter (304B, Triton Electronics, Essex, England). PO_4-P and color in the sludge filtrate were measured by the ascorbic acid method (Standard Methods 4500-P E) and the ADMI tristimulus filter method (Standard Methods 2120E), respectively, using the spectrophotometer DR/4000U with appropriate dilution. For the analysis of T-P, samples were digested by the alkaline persulfate digestion method (Standard Methods 4500E-N C). Biogas produced was analyzed by a gas chromatograph with a flame ionization detector (column: Parapak Q of 80–100 mesh and 2 m length, carrier gas: Ar at 40 mL/min, oven temp.: 40 °C, injection temp.: 120 °C, detector temp.: 120 °C; GC-9A, Shimadzu, Kyoto, Japan).