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Improvement of sludge anaerobic degradability by combined electro-flotation and electro-oxidation treatment

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ABSTRACT

Recently, bioenergy recovery from sludge biomass has attracted increasing attention due to the high demand for renewable energy resources. In order to enhance methane production from sludge biomass, electrochemical treatment can be used as a novel and efficient pretreatment for the hydrolysis of sludge biomass. In this study, a combined electro-flotation and electro-oxidation pretreatment was employed to improve the anaerobic degradability of sludge biomass. Electro-flotation was efficient in separating flocs in the mixed liquor and led to a sludge volume reduction greater than 60% after 10 min of operation at a current density of 4.72 mA cm^{-2}. Electro-oxidation using IrO_2/Ti anode was performed to improve the anaerobic degradability of sludge and resulted in a 30% increase in COD solubilization after 30 min of operation at current density of 9.45 mA cm^{-2}. The factors affecting electro-oxidation, i.e. the gap width between anode and cathode, current density and applied voltage, were investigated to optimize the operating conditions. A biochemical methane potential assay demonstrated that the anaerobic biodegradability of sludge was enhanced by combined electro-flotation and electro-oxidation pretreatment.

1. Introduction

Excess sludge produced from the activated sludge process for municipal and industrial wastewater treatment is considered an inevitable problem because its treatment and disposal accounts for up to 60% of the total operating cost of wastewater treatment plants [1]. Recently, bioenergy recovery from sludge biomass has attracted increasing interest due to the high demand for renewable energy resources. The efficiency of bioenergy recovery from sludge is closely associated with the availability of organic matters in sludge to anaerobic bacteria. In order to increase the availability of organic substances, the hydrolysis of large molecules must first be performed by disintegrating sludge flocs and disrupting microbial cell walls. Otherwise, the hydrolysis step has been shown to be the rate-limiting during anaerobic digestion of sludge [2,3]. Hydrolysis pretreatment is needed to improve the anaerobic degradability of sludge.

As a pretreatment for sludge disintegration and the disruption of microbial cell walls, electrochemical treatment is a novel and efficient tool. During the electrochemical treatment, oxidation at the anode leads to the lysis of large organic molecules associated with microbial cells. Through electrolysis, high molecular weight biopolymer substances are converted into low molecular weight products which can be easily degraded by anaerobic microorganisms. A number of theories have been proposed to explain the disruption of microbial cell wall by electrochemical reactions including electro-chlorination, destruction caused by electric field and the generation of energy-rich but short-lived intermediate products [4]. The predominant destructive action on microbial cells is thought to be mediated by the energy-rich intermediate products. OH radicals, as an example of an energy-rich intermediate product, are generated from the electrolysis of water and can completely degrade organic compounds [5,6].

The important parameters controlling the electrolysis of water and organic compounds are electrode material, current density, electrode gap between anode and cathode. Ti-supported IrO_2-based dimensionally stable anode has been reported to possess excellent electro-catalytic activity and high durability for the oxygen evolution reaction [7]. This is considered to be one of the most successful electro-catalyst in organic electro-synthesis and wastewater treatment. IrO_2 anode is believed to be less sensitive to poisoning due to simultaneous oxygen evolution. Its low over-potential for the oxygen evolution reaction can significantly reduce the surface blockade with organic substrates [8]. In this study IrO_2/Ti and Ti were used as anode and cathode, respectively. In order to increase the efficiency of electrochemical oxidation,

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Table 1
Properties of sewage sludge used in this study before electrolysis.

Parameter	Unit	Value
TSS	$mg\,L^{-1}$	7680
VSS	$mg\,L^{-1}$	5920
TCOD	$mg\,L^{-1}$	7170
SCOD	$mg\,L^{-1}$	210

the sludge thickening was performed in advance using electro-flotation. Concentrated sludge was then treated in electrochemical reactor to increase its anaerobic degradability. The parameters affecting the electrochemical oxidation of sludge were investigated to optimize the operating conditions. The anaerobic degradability of treated sludge and untreated sludge was compared using the methane formation potential test.

2. Materials and methods

2.1. Electrode preparation

The IrO_2 film electrode was used as the anode and prepared on titanium base metal by the thermal decomposition technique [8]. The precursor, $IrCl_2$ (6% solution), was dissolved in an isopropanol solution. The isopropanol solution was applied on the mechanically pretreated titanium base. The electrode was dried at 120 °C and subsequently treated at 550 °C for 30 min. The above operation was repeated three times and finally treated at 550 °C for 2 h. More details are given elsewhere [8].

2.2. Electro-flotation and electro-oxidation of sewage sludge

Samples of secondary sewage sludge were collected from the Jungryang municipal wastewater treatment plant located in Seoul, Korea. The fundamental properties of the wastewater sludge are listed in Table 1. The collected sludge was immediately transferred to the lab and stored in the refrigerator at 4 °C prior to use. A series of bench-scale experiments were conducted in the electrochemical reactor. The dimensions of the electro-flotation and electro-oxidation reactor were 17 cm (L) × 17 cm (W) × 30 cm (H). Total effective volume is 8.6 L. As shown in Fig. 1, the reactor was made of acrylic material and IrO_2/Ti mesh and Ti mesh were used as the anode and cathode, respectively. Both electrodes were made of mesh with dimensions of 14 cm × 8 cm × 0.3 cm. The effective electrode areas are 45 cm^2 for cathode and anode. Eleven electrodes (five anodes and six cathodes) were installed at 2 cm from the bottom of the reactor. The experiments were carried out using a stable power supply (5 A, 60 V DC power supply, Korea). All experiments were conducted at room temperature and the pH of the sewage sludge was not regulated. Sewage sludge was concentrated in the electro-flotation reactor and then transferred to the electro-oxidation reactor. During operation of the electro-flotation the current density was varied from 5 to 10 $mA\,cm^{-2}$ and the applied voltage varied from 10 to 20 V. Very fine bubbles were produced and used to concentrate sludge in the upper part of the reactor.

2.3. Biochemical methane potential (BMP) assay

The BMP assay can be used as an index of the anaerobic biodegradation potential [9]. The BMP is measured with the BMP assay, which consists in measuring the bio-methane or biogas produced by a known quantity of waste under batch and anaerobic conditions. Biogas productions from the raw and pretreated sludge samples were determined using batch tests under mesophilic condition. The digested sludge was withdrawn from the mesophilic anaerobic digester at the Jungryang municipal wastewater treatment plant in Seoul, Korea, and used as the inoculums for methane production. The inocula were maintained in an incubation chamber at 35 °C for 7 days to decrease the amount of residual COD. The biodegradability assays were conducted in anaerobic batch reactors of 120 mL serum bottles with hermetically sealed stoppers. Each serum bottle was filled with a solution composed of the inoculums (10 mL of digested sludge) and the pretreated excess sludge (90 mL of pretreated sludge). Serum bottles containing only the raw sludge were set as the control. The pH values in the serum bottles were adjusted to 7.0 by adding 1 M NaOH or HCl. The serum bottles were bubbled with N_2 gas to remove O_2 before being sealed with rubber stoppers and then incubated in a shaker operated at 100 rpm.

2.4. Analytical methods

The following parameters were analyzed before and after electrochemical treatment: total suspended solids (TSS), volatile suspended solids (VSS), total chemical oxygen demand (TCOD) and soluble chemical oxygen demand (SCOD). The concentrations of TSS, VSS, TCOD and SCOD were determined according to the Standard Methods for the Examination of Water and Wastewater [10]. The analyses were performed on both the sludge and the supernatant to identify the total and soluble fractions of the specific component. The COD solubilization (%) was calculated by using Eq. (1):

$$\text{COD solubilization} = \frac{\text{soluble COD (SCOD) measured after electrochemical treatment}}{\text{total COD (TCOD) measured after electrochemical treatment}} \times 100 \quad (1)$$

The gas produced from the BMP test was collected using a 100 mL syringe. Then, 250 μL of each gas sample was taken from the BMP test bottles to analyze CH_4 content by gas chromatography (GC 6000 series, Younglin, Korea) equipped with a thermal conductivity detector. Argon was used as the carrier gas at a flow rate of 30 mL/min. Gas chromatography was optimized for the analytes and the following parameters were used: oven temperature 35–210 °C (20 °C/min), injection temperature 220 °C and detector temperature 220 °C.

3. Results and discussion

3.1. Activated sludge thickening using electro-flotation

Electro-flotation produces very fine bubbles which are suitable to separate tiny flocs in the mixed liquor. The separated sludge generally showed high solids concentrations around 30,000 $mg\,L^{-1}$ [11]. Activated sludge thickening occurred during electro-flotation at a current density of 5–10 $mA\,cm^{-2}$ and an applied voltage of 10–20 V. Under these operating conditions, the anode is generally oxidized and dissolved to produce metal ions. In this study, an IrO_2-coated titanium electrode was used for electro-flotation because of its anodically insoluble property and high electrocatalytic activity for oxygen generation [12,13]. In the past decade, IrO_x-based dimensionally stable anode has received considerable attention and is also known for longer service life [14,15].

In this experiment, the operating conditions for electro-flotation, operating time and current density, were investigated to determine the sludge volume reduction efficiency. The effect of operating time on sludge volume reduction is shown in Fig. 2. A period of 10 min was found to be optimal for sludge thickening. An increase in operating time beyond 10 min did not result in greater sludge thickening because such an increase led to the production of extra useless micro-bubbles which went out of the