



# Effects of Pre-aeration on the Anaerobic Digestion of Sewage Sludge

Young-Mi Ahn<sup>1</sup>, Jun Wi<sup>2</sup>, Jin-Kyu Park<sup>3</sup>, Sotaro Higuchi<sup>4</sup>, Nam-Hoon Lee<sup>2†</sup>

<sup>1</sup>Department of Energy Business, Korea Environment Corporation, Incheon 404-708, Korea

<sup>2</sup>Department of Environmental Energy Engineering, Anyang University, Anyang 430-714, Korea

<sup>3</sup>Ecowillplus Co. Ltd., Anyang 431-779, Korea

<sup>4</sup>Recycling and Eco-Technology Specialty Graduate School of Engineering, Fukuoka University, Fukuoka 814-0180, Japan

## Abstract

The aim of this study was to assess the effect of pre-aeration on sludge solubilization and the behaviors of nitrogen, dissolved sulfide, sulfate, and siloxane. The results of this study showed that soluble chemical oxygen demand in sewage sludge could be increased through pre-aeration. The pre-aeration process resulted in a higher methane yield compared to the anaerobic condition (blank). The pre-aeration of sewage sludge, therefore, was shown to be an effective method for enhancing the digestibility of the sewage sludge. In addition, this result confirms that the pre-aeration of sewage sludge prior to its anaerobic digestion accelerates the growth of methanogenic bacteria. Removal rates for NH<sub>3</sub>-N and T-N increased simultaneously during pre-aeration, indicating simultaneous nitrification and denitrification. The siloxane concentration in sewage sludge decreased by 40% after 96 hr of pre-aeration; in contrast, the sulfide concentration in sewage sludge did not change. Therefore, pre-aeration can be employed as an efficient treatment option to achieve higher methane yield and lower siloxane concentration in sewage sludge. In addition, reduction of nitrogen loading by pre-aeration can reduce operating costs to achieve better effluent water quality in wastewater treatment plant and benefit the anaerobic process by minimizing the toxic effect of ammonia.

**Keywords:** Anaerobic digestion, Pre-aeration, Sewage sludge, Siloxane, Solubilization

## 1. Introduction

Anaerobic digestion (AD) of sewage sludge is an attractive technology for both waste treatment and energy conversion as it reduces sludge volume and produces energy-rich biogas [1]. Nevertheless, widespread application of the technology has faced three major drawbacks: long retention time, low removal rates of organic compounds, and poor operational stability of AD sewage sludge.

AD of organic materials entails a series of metabolic reactions that include hydrolysis, fermentation, and methanogenesis [2]. During hydrolysis, insoluble organic materials and complex compounds are transformed into soluble organic materials [3]. Typically, hydrolysis is the rate-limiting step in the AD of sewage sludge.

Recently, various chemical, thermal, mechanical, and biological pretreatment methods have been extensively studied to determine sludge solubilization by observing cell disruption and subsequent methane production [4]. Among those methods, biological pretreatment aims at enhancing hydrolysis via the additional biological stage prior to a main digestion process [5].

Hydrolysis can occur under both aerobic and anaerobic conditions; however, hydrolysis rates are significantly higher under aerobic conditions: this probably due to the higher production of enzymes [6].

There are typically two types of aerobic pretreatment methods: aerobic thermophilic (AT) bacteria and pre-aeration. To improve the production of biogas, AT bacteria may be more useful for AD of sewage sludge [7], but it requires the incubation of AT bacteria at 65°C.

The pre-aeration method, which takes place prior to AD, enhances hydrolysis through limited aeration [8, 9]. A ratio of extra hydrolysis to oxygen utilization is calculated to be about 0.4 mg C/mg O<sub>2</sub> [10]. Several experimental studies have assessed the effects of pre-aeration on sludge solubilization and methane production in AD [5, 6, 10]. The pre-aeration can reduce an accumulation of volatile fatty acid (VFA) in anaerobic digester, resulting in a better methanogenic phase [6]. In addition, hyperthermophilic pretreatment (60°C–70°C) is an option to increase biodegradable chemical oxygen demand content. According to



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<sup>†</sup>Corresponding Author

E-mail: nhlee@anyang.ac.kr

Tel: +82-31-467-0891 Fax: +82-31-467-0789

Hasegawa et al. [11], an increase of 50% in biogas production was observed using the hyper-thermophilic pretreatment prior to AD.

These studies reported that pre-aeration accelerated sludge solubilization and also improved methane production. However, most of these studies only reported the effects of pre-aeration and did not establish the behavior of various inhibitors including nitrogen, siloxane, and sulfide.

Hydrogen sulfide and siloxane are also found in biogas when sewage sludge contains sulfur and siloxane compounds. Therefore, additional processes for removing hydrogen sulfide and siloxane are required before transforming methane into a usable energy [1]. In addition, the presence of hydrogen sulfide and siloxane causes corrosion reducing the lifetime of equipment including gas engines, turbines, and boilers [12]. For the removal of hydrogen sulfide and siloxane from biogas, physicochemical technologies are widely employed at full scale. Under these conditions, it is possible to achieve very low hydrogen sulfide and siloxane concentrations [13]. To remove hydrogen sulfide and siloxane, however, physicochemical technologies require the use of toxic chemicals and it is expensive to operate.

Therefore, in order to investigate the possibility of reducing inhibitor loadings in anaerobic digesters and biogas purification systems, this study aims to assess the effects of pre-aeration on sludge solubilization and the behaviors of nitrogen, dissolved sulfide (S<sup>2-</sup>), sulfate (SO<sub>4</sub><sup>2-</sup>), and siloxane.

## 2. Materials and Methods

### 2.1. Materials

Sewage sludge samples for this study were collected from a wastewater treatment plant (WWTP) in Anyang, South Korea. The samples were taken from the sludge thickener and stored in a cold room at 4°C. The characteristics of the sewage sludge analyzed before the experiments are presented in Table 1.

### 2.2. Pre-aeration Conditions

The sewage sludge was pre-aerated using laboratory-scale sludge pretreatment reactors with a volume of 5 L. The reactors were filled with 3 L of sewage sludge and were operated in seven different pre-aeration conditions (Table 2). Air was supplied to all the reactors through the air stone at the bottom of the reactors at a rate of 0.15 L/min using an air compressor.

The aeration rate is expressed as volume of air per volume of sludge per minute (vvm). Considering sewage sludge of 3 L, the aeration rate is 0.05 vvm. Hasegawa et al. [11] presented two different aeration rates (0.4 and 0.08 vvm) for a hyper-thermophilic process (65°C, hydraulic retention time of 2.8 days): the aeration rate of 0.4 resulted in similar solubilization of about 40%, whereas the lower aeration rate of 0.08 vvm led to increased biogas generation compared to the higher aeration rate of 0.4 vvm.

After pre-aeration was completed, sewage sludge samples were taken for further characterization including methane generation potential.

### 2.3. Analytical Methods

The samples were analyzed for oxidation-reduction potential (ORP), dissolved oxygen (DO), chemical oxygen demand

(CODcr), soluble chemical oxygen demand (SCODcr), ammonia nitrogen concentration (NH<sub>3</sub>-N), total solids (TS), volatile solids (VS), dissolved sulfide (S<sup>2-</sup>), and sulfate (SO<sub>4</sub><sup>2-</sup>) according to the standard methods [14]. SCODcr was analyzed after filtering the sludge sample through a 0.45 μm membrane filter. Total nitrogen (T-N) was analyzed according to the Official Test Methods of Water Quality [15]. Dissolved sulfide (S<sup>2-</sup>) was analyzed by the iodometric titration method and sulfate (SO<sub>4</sub><sup>2-</sup>) was analyzed using an ion chromatograph (792 Basic IC; Metrohm AG, Herisau, Switzerland).

Siloxane is an organosilicon compound consisting of silicon, oxygen, and another functional group. Siloxanes are grouped into linear siloxane and cyclic siloxane by their molecular structure; these are denoted as “L” and “D”, respectively, in this study.

A combined extraction-analysis method was performed for determining hexamethyldisiloxane (L2), octamethyltrisiloxane (L3), decamethyltetrasiloxane (L4), dodecamethylpentasiloxane (L5), hexamethylcyclotrisiloxane (D3), octamethylcyclotetrasiloxane (D4), decamethylcyclopentasiloxane (D5), dodecamethylcyclohexasiloxane (D6) in the sewage sludge.

The 100 mL of sludge was introduced in a flask and 10 mL of n-hexane (Merck, Darmstadt, Germany) was added for extraction. The sludge-hexane mixture was vortex-mixed at a high speed for 10 min. The extracts were subsequently centrifuged at 4,400 rpm for five min. The top phase consisting of n-hexane (containing the extracted siloxane) was removed by a suction pipette [16].

Siloxane was analyzed using a gas chromatograph-mass spectrometer (GCMS-QP-2010 Ultra; Shimadzu, Kyoto, Japan) and the Restek-5MS column (30 m, 0.25 mm). For the gas chromatography conditions, temperature was set as 250°C at the injector, gas injection volume was 0.2 mL, split ratio was 5:1, and the gas flow rate was 1.5 mL/min. The oven temperature was held constant at 40°C for five minutes and then gradually increased by 15°C/min until it reached 250°C.

**Table 1.** Characteristics of sewage sludge

Characteristic	Concentration (mg/L)
CODcr	25,550
SCODcr	2,651
T-N	3,360
T-P	583
TS	30,732
VS	7,318

CODcr: chemical oxygen demand, SCODcr: soluble chemical oxygen demand, T-N: total nitrogen, T-P: total phosphorus, TS: total solids, VS: volatile solids.

**Table 2.** Experimental conditions for pre-aeration

No.	Period of pre-aeration (hr)	Amount of air (L)
1	Blank	0.0
2	0.5	4.5
3	1.0	9.0
4	6.0	54.0
5	24.0	216.0
6	48.0	432.0
7	96.0	864.0

A biochemical methane potential (BMP) test was conducted to assess the cumulative methane yield for the treated sewage sludge. The BMP test was performed in triplicate by the procedure described in Shelton and Tiedje [17]. The 14 mL of seeding sludge was added to 140 mL of the microbe medium (10:1 ratio). The amount of sample was set within 2 g-VS/L wherein methane production was not initially prohibited by the rapid accumulation of organic acids due to hydrolysis and acid-production microbes. 1 N NaOH and 1 N HCl were added to maintain pH at 7. In order to avoid any decrease in pH by acid formation and to provide sufficient alkalinity, the samples were sealed up after the addition of NaHCO<sub>3</sub> (1.2 g/L) and nitrogen purging. The test was conducted using a biochemical oxygen demand incubator at 35°C. Total amount of digestion gas production was measured regularly during the test. The concentrations of CH<sub>4</sub>, CO<sub>2</sub>, O<sub>2</sub>, and N<sub>2</sub> were analyzed using a gas chromatograph (6000M GC; Younglin, Anyang, Korea; 6'×1/4" outer & 6'×1/8" inner SS [CTR 1 Column], column 35°C, injector 120°C, detector 120°C).

### 3. Results and Discussion

#### 3.1. Effect of Pre-aeration on Sewage Sludge Characteristics

Table 3 shows the chemical characterization of sewage sludge after undergoing aeration pretreatment. AD requires strict anaerobic conditions (ORP < -200 mV). Although ORP increased with longer periods of pre-aeration, ORP maintained a range from -268 to -246 mV (Fig. 1). In addition, DO concentrations ranged from 0.00 to 0.22 mg/L because oxygen was rapidly consumed by the oxidation of organic matter. The results indicate that pre-aeration does not affect the performance of the AD process.

Fig. 2 shows SCOD<sub>cr</sub> concentration and solubilization. The effectiveness of the pre-aeration was assessed by solubilization based on the quantity of soluble organic matter, and expressed as a function of COD [18].

$$S (\%) = \frac{SCOD_f - SCOD_i}{SCOD_i} \times 100 \quad (1)$$

where S is solubilization (%), SCOD<sub>f</sub> is the final soluble chemical oxygen demand (mg/L), and SCOD<sub>i</sub> is the initial soluble chemical oxygen demand (mg/L).

An increase in the SCOD<sub>cr</sub> concentration from 2,651 to 3,287

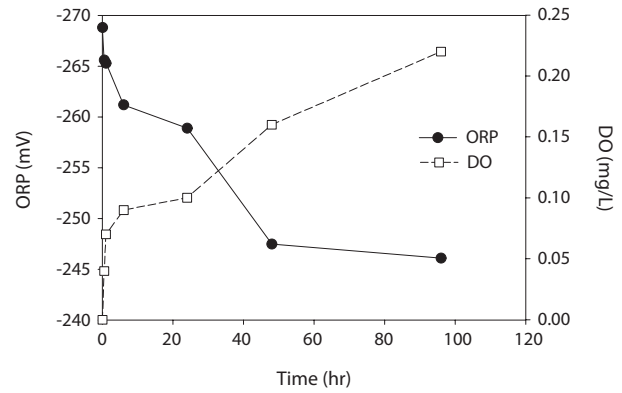


Fig. 1. Variation in oxidation-reduction potential (ORP) and dissolved oxygen (DO) concentration with the pre-aeration period.

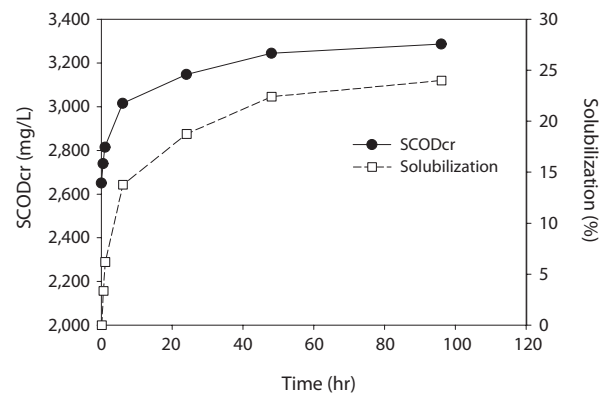


Fig. 2. Variation in soluble chemical oxygen demand (SCOD<sub>cr</sub>) concentration and solubilization with the pre-aeration period.

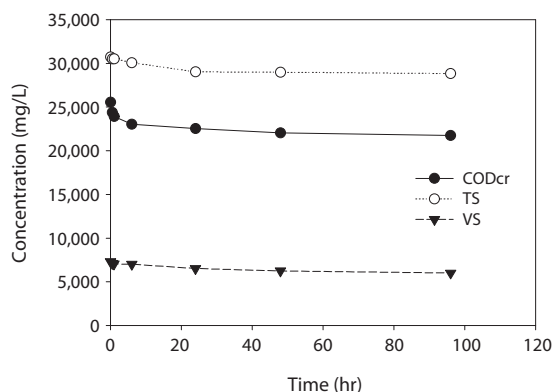
mg/L was observed when the duration of aeration was increased up to 96 hr; solubilization was estimated to be 24% in this condition. On the contrary, the concentrations of COD<sub>cr</sub>, TS, and VS decreased after the completion of pre-aeration (Fig. 3).

The results indicate that the observed increase in SCOD<sub>cr</sub> concentration after pre-aeration may originate from the disruption of microbial cells of sewage sludge, resulting in the release of various extracellular polymeric substances (EPS) [19]. In addi-

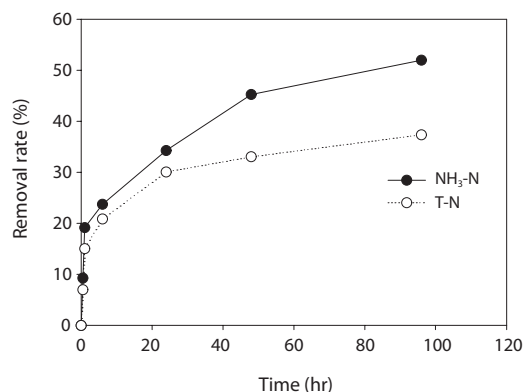
Table 3. Chemical characterization of sewage sludge after pretreatment

Item (hr)	ORP (mV)	DO (mg/L)	TCOD <sub>cr</sub> (mg/L)	SCOD <sub>cr</sub> (mg/L)	NH <sub>3</sub> -N (mg/L)	T-N (mg/L)	TS (mg/L)	VS (mg/L)
Blank	-268.80	0.00	25,550	2,651	234.3	3,360	30,732	7,318
0.5	-265.60	0.04	24,380	2,740	212.6	3,125	30,520	7,128
1	-265.30	0.07	23,920	2,815	189.4	2,855	30,502	7,052
6	-261.20	0.09	23,045	3,016	178.7	2,660	30,062	7,016
24	-258.90	0.10	22,536	3,148	154.0	2,350	29,014	6,520
48	-247.50	0.16	22,042	3,245	128.3	2,250	28,977	6,247
96	-246.10	0.22	21,747	3,287	112.5	2,105	28,822	6,008

OPR: oxidation-reduction potential, DO: dissolved oxygen, TCOD<sub>cr</sub>: total chemical oxygen demand, SCOD<sub>cr</sub>: soluble chemical oxygen demand, T-N: total nitrogen, TS: total solids, VS: volatile solids.



**Fig. 3.** Variation in concentration of chemical oxygen demand (CODcr), total solids (TS), and volatile solids (VS) with the pre-aeration period.



**Fig. 4.** Variation in removal rates of NH<sub>3</sub>-N and total nitrogen (T-N) with the pre-aeration period.

tion, the enhanced hydrolytic effect may have been undermined by a faster aerobic respiration in the presence of oxygen [20]. Johansen and Bakke [10] showed that about 50% increase in hydrolysis (based on COD) was obtained by supplying air with a rate of 500 mL/day. Carvajal et al. [21] reported that pre-aeration, which consists of subjecting a secondary sludge to a temperature of 55°C for 12 hr with a limited amount of oxygen results in a high solubilization of organic matter (40%). These results confirm that pre-aeration prior to AD does not inhibit the anaerobic process because most of the oxygen is promptly consumed for the solubilization of organic matters.

However, the changes in SCODcr concentration and solubilization were not consistent. The slopes of the solubilization and SCODcr curves decreased along with the increase of pre-aeration time from 24 to 96 hr. The solubilization levels reached 18% and 24% in 24 and 96 hr, respectively. In addition, DO concentration also increased over that time period indicating that no further significant solubilization could be expected. Therefore, it seems that optimizing the oxygen supply level for pre-aeration is required to avoid an excessive oxidation of hydrolyzed soluble products.

AD processes are vulnerable to inhibitions caused by certain accumulating chemicals, among which ammonia is the most significant inhibitor [22]. Lay et al. [23] reported that methanogenic activity dropped by 10% and 50% when ammonium-nitrogen concentrations were increased from 1,670 to 3,720 mg/L and from 4,090 to 5,550 mg/L, respectively.

Removal rates of NH<sub>3</sub>-N and T-N by the duration of pre-aeration are shown in Fig. 4. Initially, the removal rates of both NH<sub>3</sub>-N and T-N increased rapidly, indicating a simultaneous nitrification and denitrification (SND). SND means that nitrification and denitrification occur simultaneously in a reactor. According to Munch et al. [24], the DO concentration of 0.5 mg/L was suitable to achieve a nitrification rate equal to denitrification rate, which would lead to a complete SND. In this study, however, a complete SND occurred at the DO concentration of less than 0.25 mg/L.

The slopes of the removal rate for both NH<sub>3</sub>-N and T-N decreased gradually when pre-aeration time was increased from 24 to 96 hr. However, T-N had a greater rate of decrease in the removal rate of T-N than NH<sub>3</sub>-N: the removal rate of T-N reached 29% in 24 hr and 35% in 96 hr. It was evident that increasing DO concentration in sewage sludge inhibited denitrification. DO concentration greater than 0.2 mg/L significantly reduces deni-

trification rate [25].

Thus, SND by pre-aeration prior to an anaerobic digester can be very beneficial and advantageous. Conventional WWTPs primarily use anaerobic sludge digestion processes. However, large quantities of nitrogen are present in sewage sludge. Therefore, reducing the nitrogen loading with a pre-aeration may decrease the toxic effect of ammonia on methanogenic organisms; thus, it allows a WWTP to achieve a better quality in effluent.

### 3.2. Effect of Pre-aeration on Methane Yields

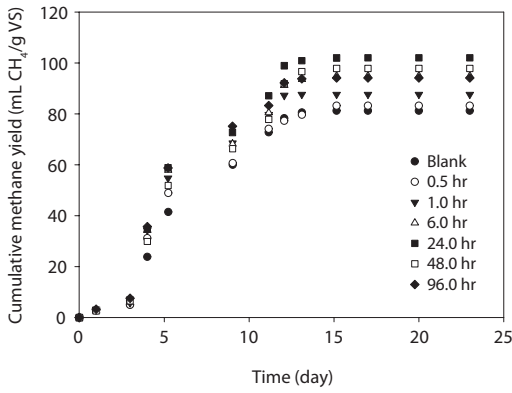
To assess the effect of pre-aeration time on AD, BMP tests with the treated sewage sludge were conducted. Cumulative methane yields measured from the BMP tests are presented in Table 4 and Fig. 5. The cumulative methane yields after pre-aeration were observed to range from 83.2 to 102.0 mL CH<sub>4</sub>/g VS, whereas that of raw sewage sludge (blank) was 81.3 mL CH<sub>4</sub>/g VS. The cumulative methane yields were higher with 24 hr pre-aerated sludge samples compared to those in other reactors. The cumulative methane yield after 24 hr of pre-aeration increased about 20% compared to the blank. These results suggest that pre-aeration has a positive effect on methane yield. According to previous studies, short-term oxygen exposure does not reduce methanogenic activity, and, in this condition, methanogens can survive longer than previously thought [26, 27].

Despite the enhanced hydrolysis (based on SCOD), however, the cumulative methane yield after the 96 hr of pre-aeration decreased compared to that after 24 hr of pre-aeration, indicating

**Table 4.** Cumulative methane yields

Period of pre-aeration (hr)	Cumulative methane yield (mL CH <sub>4</sub> /g VS)
Blank	81.3
0.5	83.2
1	87.6
6	94.9
24	102.0
48	97.9
96	94.1

VS: volatile solids.



**Fig. 5.** Variation in cumulative methane yield with the pre-aeration period.

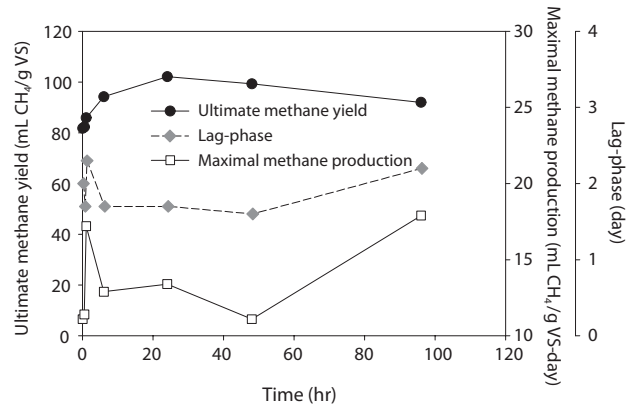
that methanogenic activity may be inhibited at DO concentrations greater than 0.15 mg/L. Decreased amounts of methane generation under increased aeration conditions have also been widely reported. According to Botheju et al. [6], the reduction of methane potential can be attributed to the substrate oxidation by facultative acidogenic organisms and the partial inhibition of the activity of strictly anaerobic biomass. Gerritse and Gottschal [28] showed that, compared to a complete anaerobic case, the rate of methane formation decreased with a limited concentration of oxygen. The range of DO concentration levels required to inhibit 50% of methanogenic activity was 4.9 to 6.4 mg/L [29]. These results indicate that optimizing the oxygen supply for pre-aeration is required in order to avoid the inhibition of methanogenic activity.

Experimental data was fitted with the modified Gompertz equation (Eq. (2)) to ease the comparison between the data [23].

$$M(t) = M_0 \cdot \exp \left[ -\exp \left( \frac{R_m \cdot e}{M_0} (\lambda - t) + 1 \right) \right] \quad (2)$$

where  $M(t)$  is cumulative methane production until  $t$  (mL CH<sub>4</sub>/g VS),  $M_0$  is methane production potential (mL CH<sub>4</sub>/g VS),  $\lambda$  is lag-phase time (day), and  $R_m$  is methane production rate (mL CH<sub>4</sub>/g VS-day).

Table 5 and Fig. 6 show the results for nonlinear regression of the cumulative methane yield using Eq. (2). The  $R^2$  values obtained via regression analysis ranged from 0.973 to 0.989, indicating that the nonlinear regression of the cumulative meth-



**Fig. 6.** Variation in regression parameters with the pre-aeration period.

ane yield fitted well with the measurements. Ultimate methane yields and maximal methane productions for pre-aeration cases were higher compared to those for the blank. The results indicate that pre-aeration enhanced the hydrolysis of sewage sludge prior to AD. However, a reduction in ultimate methane yields after 48 and 96 hr of pre-aeration was linear with period of pre-aeration. Botheju et al. [6] reported that there was a linear relationship between reduction in methane generation and oxygen load. Johansen and Bakke [10] showed that despite the enhanced hydrolysis, aerated reactors produced 50% lower methane compared to an anaerobic reactor. The results suggest that facultative organisms may generate CO<sub>2</sub> as the metabolic end product instead of the VFA under anaerobic fermentation [20]. In terms of lag-phase time, there was almost no difference among different periods of pre-aeration. This implies that an inhibitory effect of oxygen was not appeared in the early stages of the AD, which agree with the results presented by Diaz et al. [30] in the anaerobic degradation of cellulose. Thus, these results indicate that using a pre-aeration method prior to AD can accelerate the transformation of complex organic compounds found in sewage sludge into simpler organic compounds, and lead to a more efficient methane production.

### 3.3. Removal of Siloxane and Sulfur

Siloxane does not accumulate in water due to its significantly low solubility [16]. Therefore, siloxane is adsorbed more easily onto the EPS of the sludge than many other organic compounds

**Table 5.** Summary of regression parameters

Period of aeration (hr)	Ultimate methane yield (mL CH <sub>4</sub> /g VS)	Maximal methane production (mL CH <sub>4</sub> /g VS/day)	Lag-phase (day)	R <sup>2</sup>
Blank	81.8	11.1	2.0	0.989
0.5	82.3	11.4	1.7	0.978
1	85.9	17.2	2.3	0.981
6	94.2	12.9	1.7	0.973
24	102.1	13.4	1.7	0.978
48	99.3	11.1	1.6	0.978
96	92.0	17.9	2.2	0.983

VS: volatile solids.W

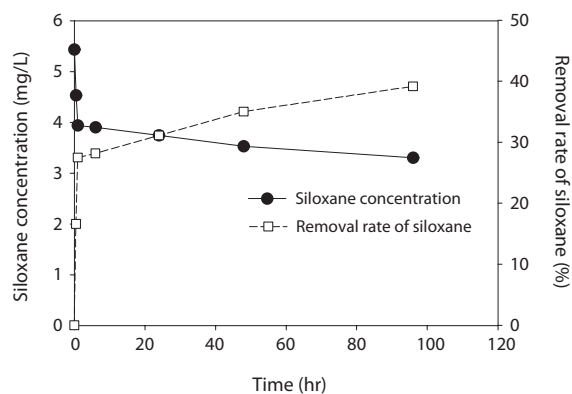


Fig. 7. Variation in removal rates of siloxane with the pre-aeration period.

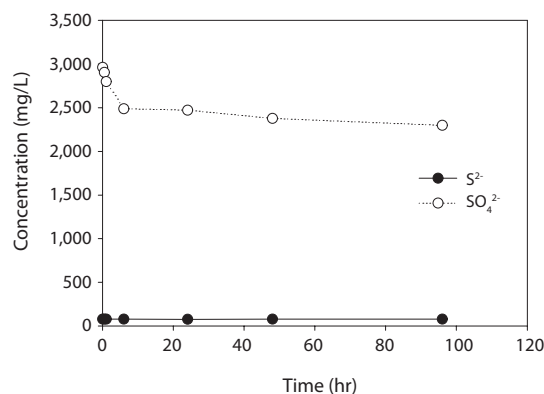


Fig. 8. Variation in concentrations of S<sup>2-</sup> and SO<sub>4</sub><sup>2-</sup> with the pre-aeration period.

[31]. During the AD, most siloxanes are released from the sludge due to the breakdown of EPS; as a result, there are siloxanes in biogas. When siloxanes are in biogas, it considerably hampers the potential use of biogas as an energy source [16]. Therefore, several studies have suggested various methods to remove siloxane from biogas, including adsorption, absorption, freezing, and biological removal [12, 32, 33]

In this study, siloxane in sewage sludge after the completion of pre-aeration was analyzed to assess the behavior of siloxane in sewage sludge during pre-aeration (Table 6). The removal rate of siloxane is given in Fig. 7; D5 was the only compound detected with concentrations ranging from 3.31 to 5.43 mg/kg. However, Dewil et al. [16] reported that only a high concentration of D4 was present in the sewage sludge from a WWTP in Fenham, UK. In contrast, Xu et al. [34] reported that D3, D4, D5, and D6 were detected in the sewage sludge obtained from a WWTP in Beijing, China. Therefore, further studies will be required to accurately assess the effects of other parameters (e.g., treatment processes of a WWTP and regional characteristics) on the concentration and distribution of siloxane.

The removal rate of siloxane in sewage sludge increased with the increase in pre-aeration duration. According to Xu et al. [34], D4 and D5 in sewage sludge may be removed by both volatilization and degradation including microbe catalysis hydrolysis. Therefore, the removal mechanism of siloxane by pre-aeration includes the breakdown of the EPS in which the siloxane is adsorbed and the subsequent release of siloxane into the atmosphere. Consequently, it seems that reduction of siloxane

loading by pre-aeration can result in lower operating costs of installed biogas purification systems.

During AD, sulfate (SO<sub>4</sub><sup>2-</sup>) was reduced to total sulfides by the biological activity of anaerobic sulfate reducing bacteria (SRB). Total sulfides produced by microbial sulfate reduction can be present in both unionized (H<sub>2</sub>S) and ionized forms (HS<sup>-</sup> and S<sup>2-</sup>) in an aqueous phase. Among these, the dissolved sulfide (S<sup>2-</sup>) can leave the aqueous phase to biogas as H<sub>2</sub>S [19]. The S<sup>2-</sup> of 200 mg/L in an anaerobic digester can cause an inhibition of methanogenesis [1]. Therefore, lowering S<sup>2-</sup> loading can reduce H<sub>2</sub>S generation potential as well as the toxic effect of S<sup>2-</sup> on methanogenic and acetogenic organisms during AD of sewage sludge [4, 35].

The S<sup>2-</sup> and SO<sub>4</sub><sup>2-</sup> concentrations after pre-aeration are shown in Fig. 8. The S<sup>2-</sup> levels remained almost constant after pre-aeration, whereas the SO<sub>4</sub><sup>2-</sup> levels decreased slightly. It indicates that the amount of oxygen supplied in this study was insufficient to oxidize S<sup>2-</sup> because oxygen supplied in the reactor was only consumed for the oxidation of organic material and nitrification.

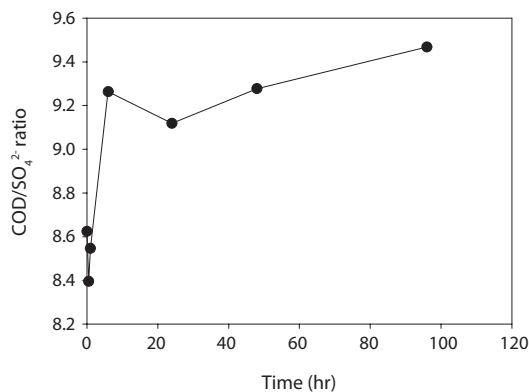
The COD/SO<sub>4</sub><sup>2-</sup> ratio is an important factor that determines the competition between methane producing microorganisms (MPM) and SRB [36]. Choi and Rim [37] reported that acetoclastic MPM were dominant species when the COD/SO<sub>4</sub><sup>2-</sup> ratio was above 2.7 while SRB predominated when this ratio was below 1.7. Sarti and Zaiat [38] showed that sulfate reduction inhibited methanogenesis and induced excessive sulfide production when the COD/SO<sub>4</sub><sup>2-</sup> ratio was 3.65 and the sulfate concentration was 2,000 mg/L.

In this study, the COD/SO<sub>4</sub><sup>2-</sup> ratios after the completion of

Table 6. Siloxane concentrations

Period of aeration (hr)	Siloxane (mg/kg)								
	L2	L3	L4	L5	D3	D4	D5	D6	Total
Blank	ND	ND	ND	ND	ND	ND	5.43	ND	5.43
0.5	ND	ND	ND	ND	ND	ND	4.53	ND	4.53
1	ND	ND	ND	ND	ND	ND	3.94	ND	3.94
6	ND	ND	ND	ND	ND	ND	3.90	ND	3.90
24	ND	ND	ND	ND	ND	ND	3.74	ND	3.74
48	ND	ND	ND	ND	ND	ND	3.53	ND	3.53
96	ND	ND	ND	ND	ND	ND	3.31	ND	3.31

ND: not detected.



**Fig. 9.** Variation in COD/SO<sub>4</sub><sup>2-</sup> ratio with the pre-aeration period. COD: chemical oxygen demand.

the pre-aeration were estimated to range from 8.4 to 9.5 (Fig. 9). Although SO<sub>4</sub><sup>2-</sup> concentration was more than 2,000 mg/L, it seemed that the SO<sub>4</sub><sup>2-</sup> inhibition to the growth of MPM during AD was very low owing to the high COD/SO<sub>4</sub><sup>2-</sup> ratio.

In addition, the COD/SO<sub>4</sub><sup>2-</sup> ratio increased as SO<sub>4</sub><sup>2-</sup> concentration decreased. It implies that, during the pre-aeration, increasing SCOD concentration resulted in the increasing amount of organic matters, which can be used as electron donors by SRB. For SO<sub>4</sub><sup>2-</sup> removal, organic matters, such as butanol, are required an electron donor [38]. Therefore, pre-aeration can reduce sulfur (S) loading in sewage sludge, which can reduce H<sub>2</sub>S generation potential during AD.

#### 4. Conclusions

The aim of this study was to assess the effect of pre-aeration on sludge solubilization and the behaviors of nitrogen, dissolved sulfide, sulfate, and siloxane. Pre-aeration of 10 sewage sludge for converting particulate matters into soluble contents was effective in enhancing the digestibility of the sewage sludge. In addition, the pre-aeration of sewage sludge prior to AD accelerated the growth of methanogenic bacteria, which was confirmed by measuring the methane production. Despite the enhanced hydrolysis (based on SCOD), however, some methanogenic activity was inhibited by the presence of dissolved oxygen. Thus, optimizing the oxygen supply for pre-aeration is required to avoid inhibition to the methanogenic activity. Removal rates of NH<sub>3</sub>-N and T-N increased simultaneously during pre-aeration, indicating SND. However, denitrification can be inhibited at DO concentration greater than 0.2 mg/L. The removal rate of siloxane in sewage sludge increased with an increase in pre-aeration time. The removal mechanism of siloxane by pre-aeration is explained by the breakdown of the EPS in which the siloxane is adsorbed, and the subsequent release of siloxane into the atmosphere. Therefore, we suggest the pre-aeration process as an efficient treatment option for achieving higher methane yields and lower siloxane concentration in sewage sludge. Finally, reducing nitrogen loading using pre-aeration can reduce operating costs, help achieve a better effluent water quality in WWTPs, and improve the efficiency of anaerobic digesters by minimizing the toxic effect of ammonia.

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