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Research Article

Effect of Volatile Fatty Acid Concentration on Anaerobic Degradation Rate from Field Anaerobic Digestion Facilities Treating Food Waste Leachate in South Korea

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The purpose of this study was to investigate the effect of volatile fatty acid concentration on anaerobic degradation rate of food waste leachate in the anaerobic digestion facilities. The anaerobic digestion facilities treating food waste leachate (FWL), codigestion with food leachate and animal manure (A-MIX), and codigestion with food waste leachate and sewage sludge (S-MIX) were selected for this study. In accordance with the regulation under Wastes Control Act in South Korea, the guideline of volatile solid removal rate for anaerobic digestion facility is set as 65% for anaerobic degradation efficiency. Highest volatile solids removal rates were achieved from FWL (63.5%) than A-MIX (56.4%) and S-MIX (41.2%). Four out of eight FWLs met the guidelines. The concentration of volatile fatty acids, therefore, was analyzed to determine the relationship with volatile solid removal rate. The results showed that, in order to meet the Korean guideline of 65% volatile solid removal rate, volatile fatty acid concentrations should remain below 4,000 mg/L on the field anaerobic digestion facilities treating FWL. Volatile fatty acid concentrations should be used along with others as an operational parameter to control and manage the anaerobic digestion process.

1. Introduction

Before ban of direct landfill of food waste was imposed in South Korea, more than 90% of food waste was landfilled and the rest was treated by composting, incineration, feeding livestock, and anaerobic digestion [1, 2]. Landfilling of food waste has been banned in Korea since 2005 because of problems of leaching and odour from landfilling of food waste [1, 3]. Ocean dumping of food wastes has also been banned since 2012 in compliance with the London Convention and Protocol [4]. Effective treatment option for organic waste has been sought thereafter.

Anaerobic digestion treatment has been one of the effective treatment options for biodegradable organic waste including food waste/food waste leachate, animal manure, and sewage sludge as it effectively reduces the amount of organic waste and produces biogas as a renewable energy [3, 5].

Food waste is a good resource for anaerobic digestion treatment because it contains high organic matter with appropriate moisture content [2] and it is easily biodegradable [3, 6]. Animal manure provides high buffering capacity [7]; therefore, it has been often treated by anaerobic codigestion with sewage sludge and/or food waste [8–10]. Because of its low concentration of organic matters, sewage sludge has been known to produce low amount of biogas compared to anaerobic digestion of food waste and animal manure [2]. It often has been treated by anaerobic codigestion with food waste to improve anaerobic degradation efficiency [2]. There have been many studies on improving its degradation efficiency by anaerobic codigestion of animal manure and sewage sludge with food waste. Some of them are on anaerobic codigestion system with food waste, animal manure, and sewage sludge [10], anaerobic digestion system with food waste and sewage sludge [11–13], and anaerobic codigestion system with food waste and animal manure [14, 15]. These studies were based on bench- or pilot-scales. More analysis of the process in the actual facilities is required to understand and monitor the efficiency.

There currently are 57 anaerobic digestion/codigestion facilities nationwide, and they are either at conventional wastewater treatment plants or at separate anaerobic digestion/codigestion plants for the organic fraction of municipal solid waste (OFMSW), mainly food waste/food waste leachate in South Korea [16].

Anaerobic digestion involves a series of metabolic reactions (hydrolysis, acidogenesis, and methanogenesis) [17, 18]. Among these intermediate products of anaerobic digestion, two volatile fatty acids (acetic acid and butyric acid) are among the most favored for methane formation while acetic acid contributes more than 70% to the methane formation [19]. Namely, acetic acid, butyric acid, isobutyric acid, isovaleric acid, and propionic acid have been known as good indicators for monitoring performance of anaerobic digestion process, especially in the activity of acetogenic and methanogenic bacteria [17, 19–22]. Additionally, various physicochemical parameters (pH, temperature, alkalinity, volatile fatty acid, retention time, biogas, etc.) influence these reactions [23–25]. The complexity of the process made the interpretation of the performance of the process difficult; therefore a combination of those parameters was suggested as a better method for monitoring the performance of the process [26].

In South Korea, the anaerobic digestion facilities treating food waste and food waste leachate have been regulated by the Wastes Control Act and volatile solid removal rate for anaerobic digestion facility is set as 65% in accordance with the guidelines for anaerobic degradation efficiency [16].

Therefore, the objective of this paper was not only to identify the parameters that can be used to determine the performance of the anaerobic digestion process in terms of anaerobic degradation efficiency in South Korea but also specifically to investigate the effect of the volatile fatty acid concentration on anaerobic degradation rate of food waste leachate in these anaerobic digestion facilities.

2. Materials and Methods

2.1. Selection of Facilities and Sampling. Seventeen anaerobic digestion/codigestion facilities at conventional wastewater treatment plants and at separate anaerobic digestion/codigestion plant for OFMSW were selected for this investigation. These facilities were treating more than 50 t/d of feedstock rate. They include 8 facilities treating food waste leachate (FWL 1~FWL 7), 3 anaerobic codigestion facilities with a mixture of animal manure and food waste leachate (A-MIX 1~A-MIX 3), and 6 anaerobic codigestion facilities with a mixture of sewage sludge and food waste leachate (S-MIX 1~S-MIX 6). The types of feed waste and the digestion system were presented in Table 1.

Samples for analysis were collected from the inlet and outlet valves of anaerobic digester at each facility. And they were kept refrigerated until they were analyzed.

2.2. Analytical Methods. Total solids, moisture content, and volatile solids were determined according to Standard Methods 1684 [26]. CODcr was analyzed according to closed reflux, titrimetric method (5220 C) and NH_4^+-N and T-N were analyzed according to Standard Methods 4500 [26] and standard methods for testing water [35].

Volatile fatty acids were analyzed according to Standard Methods (5560 D-Gas chromatographic method) [26, 36, 37]. The concentration of each volatile fatty acid, namely, acetic acid, propionic acid, isobutyric acid, butyric acid, isovaleric acid, and valeric acid, was conducted by gas chromatography (Agilent 6890, USA; column: DB-FFAP, 25 m × 0.32 mm × 0.5 μm; oven temperature program: 2 min, 95°C, 2 min, 140°C at 10°C/min, and 5 min, 240°C at 40°C/min; injection temperature: 240°C; injection mode: split (10 : 1); flow: 1.0 mL/min) equipped with FID detector. Helium was used as a carrier gas. Samples were acidified to pH 2 with phosphoric acid and centrifuged at 3500 rpm for 5 min. The supernatant was extracted with 1 g of NaCl and diethyl ether after vortexing for 5 min before being analyzed with GC-FID.

3. Results and Discussion

3.1. Characteristics of Feed Waste. Table 2 shows the physicochemical characteristics of feed wastes. The moisture content, fixed solids, and volatile solids of individual feed waste were presented in Figure 1. Total solids content in FWL from 8 anaerobic digestion facilities varied from 3.6% to 12.2% with the average total solids content of 7.2%. Volatile solid content in FWL from 8 anaerobic digestion facilities varied from 1.8% to 10.4% with the average volatile solid content of 5.5%. Total solid content in A-MIX from 3 anaerobic digestion facilities varied from 4.3% to 5.3% with the average total solid content of 4.6%, and volatile solid content in A-MIX from 3 anaerobic digestion facilities varied from 3.0% to 3.7% with the average volatile solid content of 3.3%. Total solid content in S-MIX from 6 anaerobic digestion facilities varied from 3.1% to 9.4% with the average total solid content of 5.0%, and volatile solid content in S-MIX from 6 anaerobic digestion facilities varied from 2.0% to 7.4% with the average volatile solid content of 3.5%. The highest total solid and volatile solid content were from FWL as expected. The volatile solid content in total solids (volatile solid/total solids) from all types of feed wastes was 71.0, 72.0, and 71.5% for FWL, A-MIX, and S-MIX, respectively. Volatile solid/total solid presents the amount that is biodegradable in total solid. The physicochemical characteristics of three types of feed waste from the literature are presented in Table 3. Borowski and Weatherley [38] also observed similar percentage of volatile solid in total solid (volatile solid/total solids) for poultry manure and sewage sludge, even though animal manure contained higher total solid and volatile solid than those in sewage sludge. Volatile

Table 1: Operating conditions of selected anaerobic digestion facilities.

Types of feed waste	Individual anaerobic digestion facility	Mixing ratio*	T (°C)	Types of system**
Food waste leachate (FWL)	FWL1	1	55	2
	FWL2	1	35	2
	FWL3	1	35	—***
	FWL4	1	35	1
	FWL5	1	35	—
	FWL6	1	55	1
	FWL7	1	55	—
	FWL8	1	—	2
Animal manure + food waste leachate (A-MIX)	A-MIX1	3 : 1†	35	1
	A-MIX2	7 : 3	55	1
	A-MIX3	—	35	2
Sewage sludge + food waste leachate (S-MIX)	S-MIX1	3 : 2‡	55	1
	S-MIX2	13 : 1	35	1
	S-MIX3	4.5 : 1	35	2
	S-MIX4	4 : 1	35	1
	S-MIX5	50 : 1	55, 35	1
	S-MIX6	6.7 : 1	35	1

*Ratio = feed ratio into anaerobic digester. †Animal manure: food waste leachate for A-MIX, ‡sewage sludge: food waste leachate for S-MIX.
**1: single stage system; 2: two-stage system.
***—: unknown data.

Table 2: Physicochemical characteristics of feed waste.

Parameters	Unit	Types of feed waste FWL	A-MIX	S-MIX
Moisture content	%	92.8 (2.9)	95.4 (0.5)	95.0 (2.1)
Volatile solid	%	5.5 (3.0)	3.3 (0.3)	3.5 (1.8)
Total solids	%	7.2 (2.9)	4.6 (0.5)	5.0 (2.1)
Volatile solid/total solids*	%	71.0 (15.1)	72.0 (1.1)	71.5 (9.5)
T-N	mg/L	3,190.5 (953.0)	4,744.0 (5,260.0)	4,914.4 (2,406.0)
NH_3-N	mg/L	686.7 (749.3)	777.1 (979.9)	98.8 (372.0)
Total volatile fatty acid	mg/L	12,420.0 (9,878.9)	9,115.0 (2,957.5)	3,679.5 (4.6)

Mean values of 17 selected facilities and standard deviation in parentheses.
(n = 8 for FWL, n = 3 for A-MIX, and n = 6 for S-MIX.)
*Volatile solid/total solids = [Volatile solid/(Volatile solid + Fixed solid)] × 100.

solid/total solids for fruit and vegetable wastes and food wastes in the literature (Table 3) were in the range of 82.5~92.9% and they were higher than those found in this study. The discrepancy could be related to the different composition of food waste because of food/dietary habit in different geographical background. In addition many of food wastes and fruit and vegetable wastes were collected from one place, that is, restaurant or cafeteria which might produce the wastes with less variation than those from the municipal solid waste facilities. The physicochemical characteristics of S-MIX (5.0% of total solids and 3.5% of volatile solid) in this study were higher than those of sewage sludge (3.5~4.9% of total solids and 2.3~3.7% of volatile solid) in the literature (Table 3) because S-MIX in this study was mixed with food waste leachate.

3.2. Removal Rates of Volatile Solid and COD. The volatile solid removal rate from each anaerobic digestion facility with individual feed waste is presented in Figure 2. The guideline of anaerobic degradation efficiency in South Korea is stipulated to monitor the efficiency of the process. Figure 2(a) shows volatile solid removal rates of 17 anaerobic digestion facilities and the bold horizontal dashed line denotes the volatile solid removal rate of 65% as set forth in Wastes Control Act. Considering the types of feed waste, the average volatile solid removal rate of FWL was 63.4%, and it was higher than volatile solid removal rate of A-MIX (56.4%) and S-MIX (41.2%). Regarding FWL, 4 out of 8 anaerobic digestion facilities with food waste leachate achieved volatile solid removal rates greater than 65% and they were ranged from 78 to 88%. Two out of 8 facilities with FWL achieved volatile

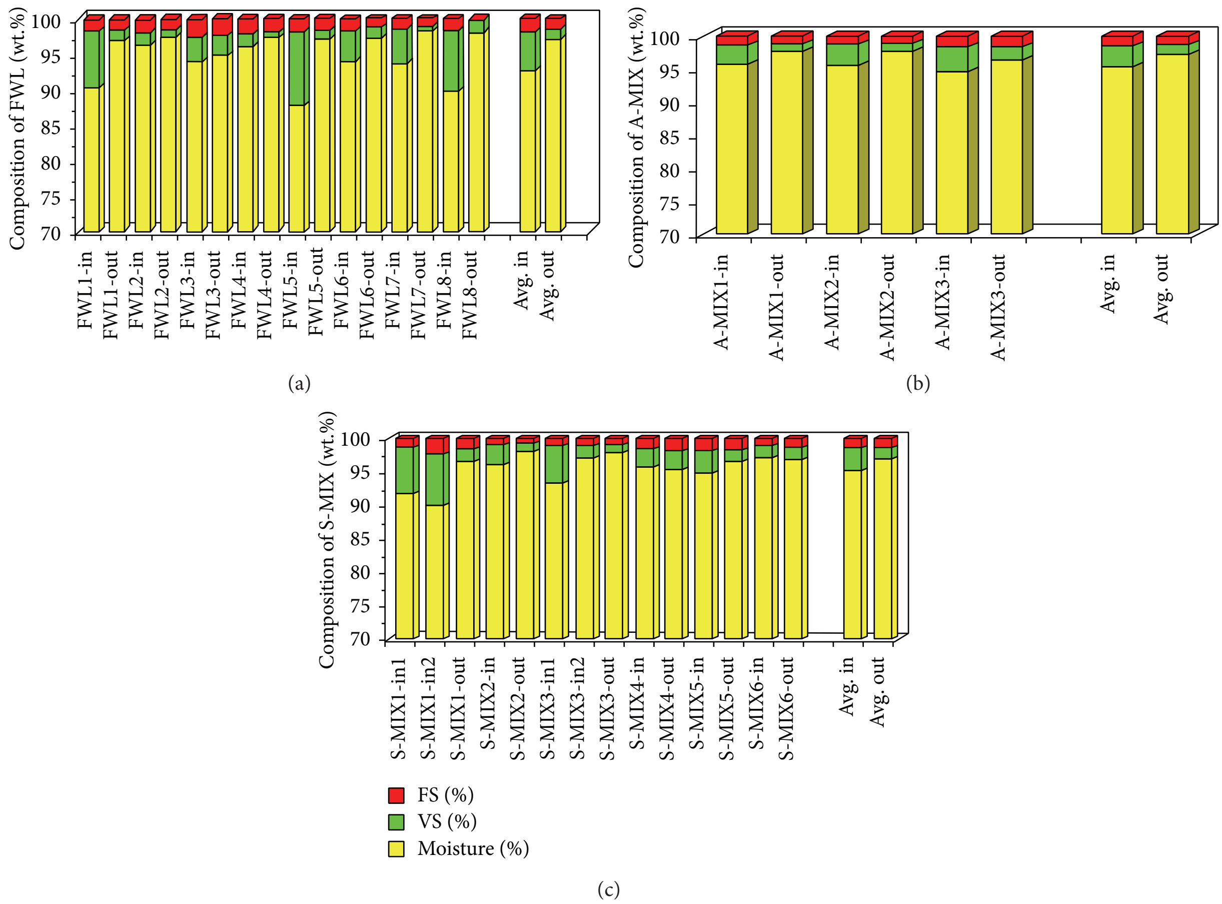

Figure 1: Compositions of feed waste: (a) FWL; (b) A-MIX; (c) S-MIX.

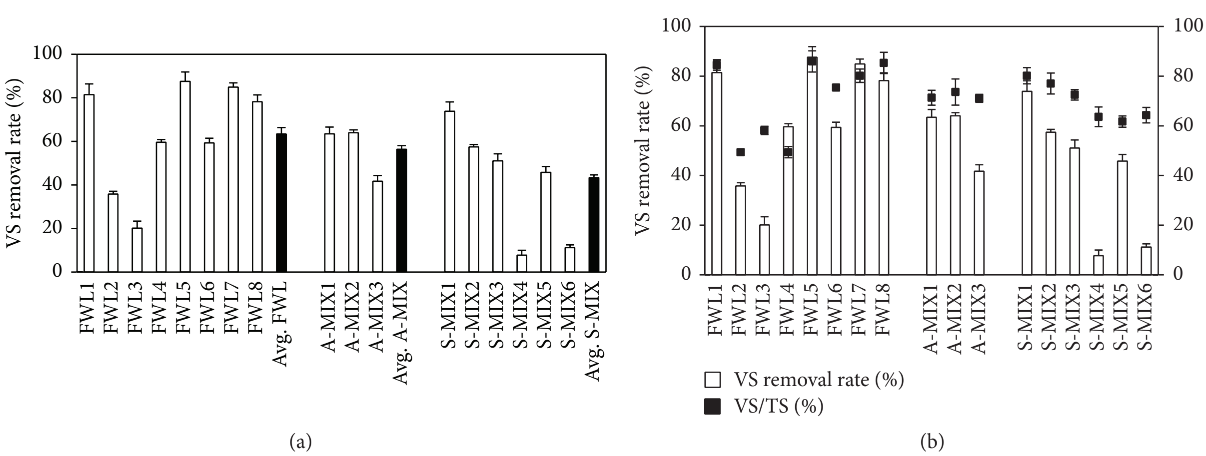

Figure 2: Volatile solid removal rates of individual anaerobic digestion facilities: (a) comparison with 65% volatile solid removal rate of Korea Waste Act; (b) comparison with volatile solid/total solids.

solid removal rate just below 65% (59 and 60%). Regarding A-MIX, 2 out of 3 facilities reached volatile solid removal rate just below 65% (63 and 64%). Regarding S-MIX, 1 out of 6 facilities with S-MIX reached volatile solid removal rate over 65% (74%) and 3 out of 6 facilities with S-MIX operated at the volatile solid removal rate of 51~57%.

Lee et al. [2] obtained a similar result of volatile solid removal rate ranging between 46.6 and 61.7% from a bench-scale anaerobic codigestion reactor with food waste and sewage sludge. Reasonably high volatile solid removal rates with the range of 39.5~86.1% were observed from food waste in the literature (Table 3) and they are comparable

Table 3: Total and volatile solid of food waste, animal (poultry, pig, and cow) manure, and sewage sludge and their VS removal rates in the literature.

Waste	Total solids (%)	Volatile solid (%)	Volatile solid/total solids (%)	Volatile solid removal rate (%)**	References
Poultry manure	28.9 27.7	21.5 20.5	72.7 74.0	43.1~49.4 (with sewage sludge)	KMOE [16], McCarty and Smith [27]
Pig manure	9.2	7.0	76.1	—	Borowski et al. [28]
	12.4	9.0	72.6	23.9~32.5 (with sewage sludge)	
Cow/dairy manure	26.7	22.5	84.3	—	Anjum et al. [29]
	13.8	11.0	79.9	—	Scano et al. [30]
	17.1 9.2	16.3 13.2	84 81	— —	Zhang et al. [15]
Fruit and vegetable wastes	12.7	11.0	86.6	—	Anjum et al. [29]
	3.4~21.8	2.7~20.4	—	—	Borowski et al. [28]
	4.4~4.5	3.9~4.0	—	53 (no pH control)	Ganesh et al. [31]
	7.3~10.0	9.7	—	70 (with pH control)	An et al. [6]
Composite food waste (grain, fish, meat, fruit, and vegetable)*	27.5	22.7	82.5	—	Lee et al. [2]
	3.0~4.5	2.9~4.3	—	—	Ganesh et al. [31]
	22.4	18.9	84.4	39.5 (with activated waste sludge and mesophilic)	El-Mashad and Zhang [32]
	18.0~23.0	16.4~21.9	—	74.1~86.1	Kim et al. [12]
	7.0~20.0	6.6~19.0	—	—	Cabbai et al. [33]
	28.0	24.1	85.0		Scano et al. [30]
	30.9	26.4	92.0	—	Cabbai et al. [33]
	18.5	17.0	92.9	—	Zhang et al. [15]
	24.8	23.0	—	68.3~80.6	Cavinato et al. [34]
Sewage sludge	4.7~4.9	3.5~3.7	74.1	33.9~36.3	KMOE [16], McCarty and Smith [27]
	3.5	2.3	65.7	—	Ganesh et al. [31]
	3.8	2.3	60.5	—	El-Mashad and Zhang [32]

Only those types of waste relevant to the Korean dietary habit were considered and those green wastes (grass, wood, etc.) were not included.
*Composite food wastes were mainly collected from household, restaurant, canteen, and cafeteria.
**Pilot-scale and lab-scale; —: data unavailable.

with volatile solid removal rate of FWL (avg. 63.5%) in this study. The second highest volatile solid removal rates were achieved with A-MIX (avg. 56.4%) in this study and the result was higher than the volatile solid removal rate with animal manure in the literature (23.9~49.4%). The lowest volatile solid removal rate was observed from S-MIX (avg. 41.2%) and the result was also higher than the result in the literature (26.8~38.2%). The reason for higher volatile solid removal rates observed from A-MIX and S-MIX in this study was due to the codigestion with food waste leachate. The result surely could not be directly compared with the results in the literature due to different operational systems and conditions; however the trend in volatile solid removal rate achieved from food waste leachates in this study was comparable with the results in the literature (Table 3).

Higher volatile solid generally means higher amount of organic materials that are convertible to biogas. Also higher volatile solid/total solids increased the amount of biodegradable materials and it would cause the increase of the microbial activities, thereby increasing volatile solid removal rate [38]. Figure 2(b) indicated a reasonable trend of increasing volatile solid removal rates with increasing volatile solid/total solids. In the current study, volatile solid/total solids of three types of feed waste, such as FWL, A-MIX, and S-MIX, were analyzed within the average range of 71.0~72.0% and they agreed with volatile solid/total solids in the literature (Table 3). Therefore the performance of anaerobic digestion was related to the volatile solid/total solids.

COD concentrations of input and output of each anaerobic digestion facility are presented in Figure 3. Average COD concentration of FWL in inlet ("FWL-In") was 85,169 mg/L, average COD concentration of A-MIX in inlet ("A-MIX-In") was 80,267 mg/L, and average COD concentration of S-MIX in inlet ("S-MIX-In") was 64,033 mg/L. After anaerobic

Table 4: Results of COD and VS removal rate.

Types of feed waste	Individual anaerobic digestion facility	CODcr removal rate (%)	VS removal rate (%)
FWL	FWL1	79 ± 5	81 ± 6
	FWL2	58 ± 2	36 ± 3
	FWL3	14 ± 1	20 ± 3
	FWL4	72 ± 3	60 ± 5
	FWL5	92 ± 6	88 ± 3
	FWL6	53 ± 4	59 ± 4
	FWL7	83 ± 3	85 ± 4
	FWL8	78 ± 4	78 ± 3
	Mean ± SD#	**66 ± 13**	**63 ± 23**
A-MIX	A-MIX1	35 ± 2	63 ± 3
	A-MIX2	83 ± 6	64 ± 6
	A-MIX3	71 ± 5	42 ± 4
	Mean ± SD#	**63 ± 20**	**56 ± 10**
S-MIX	S-MIX1	83 ± 3	74 ± 5
	S-MIX2	65 ± 5	57 ± 2
	S-MIX3	51 ± 5	51 ± 4
	S-MIX4	85 ± 6	8 ± 1
	S-MIX5	39 ± 4	46 ± 3
	S-MIX6	24 ± 3	11 ± 1
	Mean ± SD#	**58 ± 18**	**41 ± 24**

#Mean ± standard deviation.

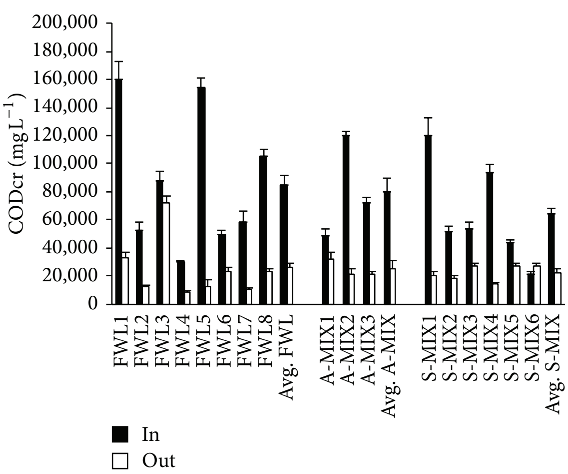

Figure 3: CODcr of each anaerobic digestion facility.

digestion treatment, COD removal rates for FWL, A-MIX, and S-MIX were found to be 66.1%, 62.6%, and 57.8% (Table 4), respectively.

Although there is still a debate about whether the volatile solid removal rate of 65% set forth in Wastes Control Act is reasonable, the results from 17 anaerobic digestion facilities in South Korea agreed with those of the literature that the highest removal rate was observed with food waste while the lowest removal rate was observed with sewage sludge (Table 4).

3.3. Relationship between Volatile Fatty Acid Concentration and Anaerobic Degradation Rate. Figure 4 shows the concentration of 6 individual volatile fatty acids, namely, acetic acid, propionic acid, isobutyric acid, butyric acid, isovaleric acid, and valeric acid, found in inlet and outlet of each anaerobic digestion process. For FWL, the concentration of acetic acid was highest in feed waste, and the average concentration of acetic acid was 5,431 mg/L. The high concentration of butyric acid was observed from feed waste of FWL2 and FWL3 (6,014 and 9,049 mg/L, resp.) and high concentration of propionic acid was also observed from feed waste of FWL2 and FWL4 (2,065 and 2,248 mg/L, resp.). This result agreed with Wijekoon et al. [19] who observed acetic acid and butyric acid as the predominant volatile fatty acid. High concentrations of propionic acid were relatively found in outlet from FWL2, FWL3, FWL4, and FWL6 (569, 1,282, 1,795, and 847 mg/L, resp.). For A-MIX, the concentration of acetic acid was dominantly high in feed waste with the average concentration of 3,925 mg/L. Concentration of propionic acid was high (average concentration of 1,751 mg/L) in outlet of A-MIX3. For S-MIX, the concentration of acetic acid was observed to be the highest in feed (average of 2,218 mg/L). The highest concentration of acetic acid was observed from one of the inlets (denoted as "S-MIX3-In1" in Figure 4) of S-MIX3 (11,213 mg/L) where food waste leachate was fed into the anaerobic digester (S-MIX3-In1) separately and sewage sludge was fed through other inlet (denoted as "S-MIX3-In2" in Figure 4) of S-MIX3. Acetic acid has been known as an important intermediate for overall anaerobic digestion process as it is directly related to the end product, methane, and carbon dioxide [17, 19], and propionic acid was important for supplying electron flow [17]. Gorris et al. [17] noticed that complete degradation of propionic acid was observed when low concentration of acetic acid (less than 100 mg/L) existed and high concentration of acetic acid (4,700 mg/L) blocked the degradation of propionic acid. Many agreed that higher concentration of acetic acid inhibited the degradation of propionic acid [17, 21] and inhibited the acetate-utilizing

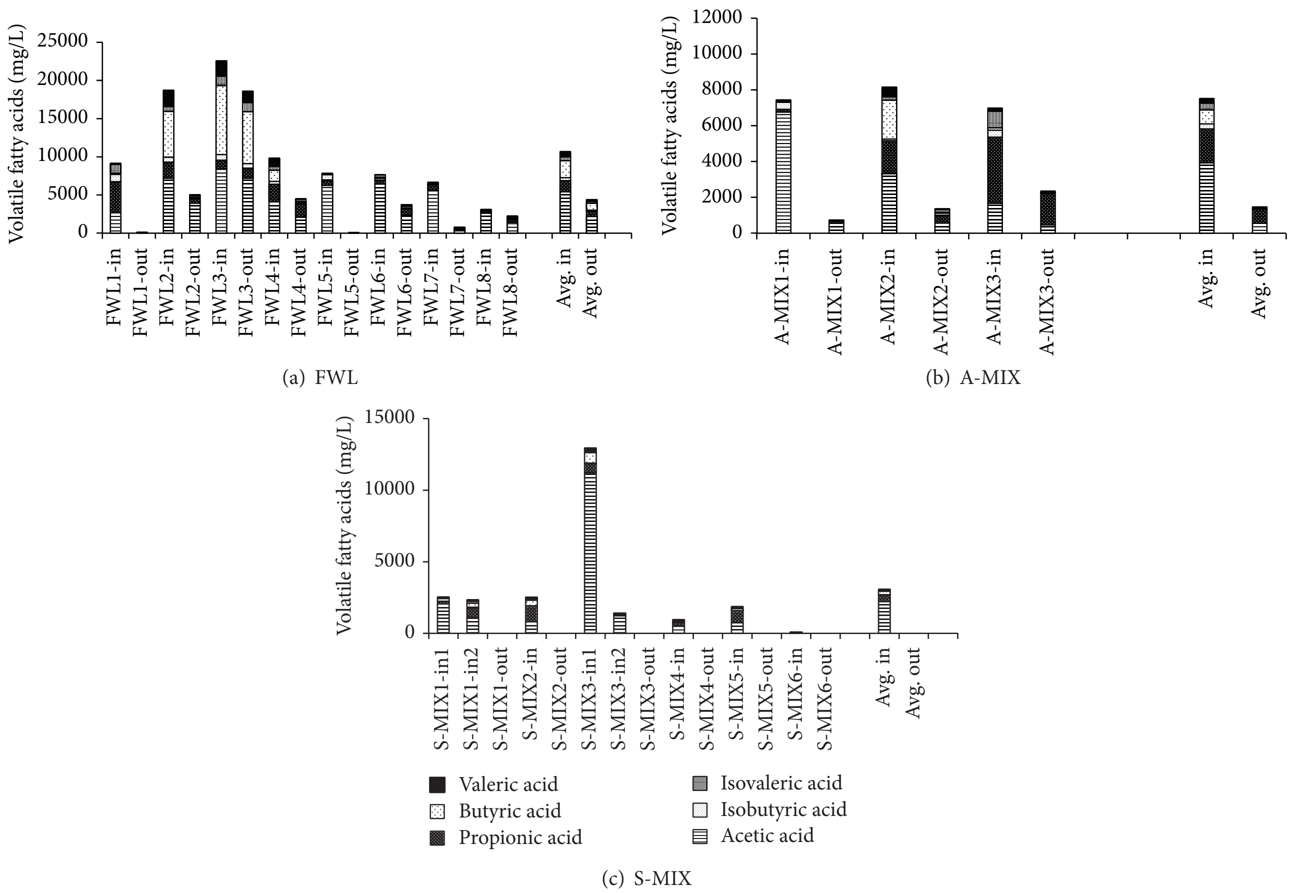

Figure 4: Volatile fatty acids from each anaerobic digestion facility with different feed wastes.

methanogenic bacteria [39]. The accumulation of propionic acid might indicate the sign of disturbance of the process [17, 23, 40]. Björnsson et al. [23] reported that accumulation of propionic acid is closely related to the concentration of hydrogen; therefore hydrogen concentration could be a possible parameter to monitor the accumulation of volatile fatty acid [23, 26]. Some studies have found that propionic acid should be treated as a toxic volatile fatty acid in anaerobic digester and the methanogenic bacteria have been shown vulnerable to propionic acid concentration greater than 1,000~2,000 mg/L [19]. Although Gourdon and Vermande [41] observed no inhibitory effect of propionic acid even at 6,000 mg/L they agreed that the accumulation of propionic acid should be seen as the warning sign and should take the attention of the process before it would cause a disturbance. Also Ahring et al. [22] suggested that volatile fatty acid should be used as indicators of imbalance of the process rather than an inhibitor. Therefore the volatile fatty acid should be treated as a monitoring parameter rather than an inhibitor.

Direct comparison with the literature was impossible in this study due to different system and operational conditions; however the effect of acetic acid on degradation of propionic acid and resulting production of methane as the end product has been reported. McCarty and Smith [27] suggested that the propionic acid accumulation appeared to predominate in the complex waste and the high concentration of propionic acid in FWL and A-MIX might be related to this finding. Several studies have found that OFMSW tended to produce long volatile fatty acids due to the presence of high level of protein and fat contents and they can lead to operational problems and instability of the digestion performance; therefore codigestion is recommended to alleviate this adverse effect and improve the efficiency of the process [15, 27]. Volatile solid removal rate of FWL3 was lowest, and this might indicate instability of the digestion performance and the methanogenic bacterial activity. Further study is required to conclude the effect; however better degradation of propionic acid has been noticed when lower concentration of acetic acid was found in S-MIX.

Figure 5 shows the relationship between volatile fatty acid concentration and volatile solids removal rate on the FWLs. It showed a linear relationship between volatile fatty acid concentration and volatile solid removal rate. According to this linear relationship, volatile fatty acid concentration should be below 4,000 mg/L in order to meet the Korean guideline of 65% volatile solid removal rate on the FWL. As A-MIX and S-MIX were without the guideline of volatile solid removal rate as well as with very low volatile solid removal rate, this relationship was analyzed except for them. In addition, the average volatile fatty acids of even the inlets of A-MIX and

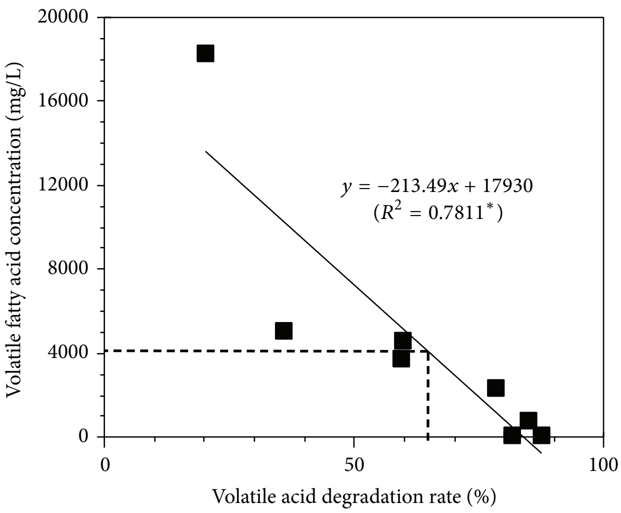

Figure 5: Relationship between volatile solid removal rate and volatile fatty acid concentration. ∗ denotes significance at 5.0% level.

S-MIX were very lower, approximately 1/2~1/4, compared to the volatile fatty acids of FWLs (Figure 4). Therefore without considering 65% of volatile solid removal rate, limiting volatile fatty acid concentration to below 4,000 mg/L still seemed a reasonable approach to control the performance of the anaerobic digestion process. However considering 4 facilities (FWL) with volatile solid removal rate that were higher than 70%, below 4,000 mg/L should be recommended. This relationship was observed from this specific study and it might not be applicable to all. More detailed study of each volatile fatty acid component is necessary to underpin the effect of the volatile fatty acid concentration on anaerobic degradation rate of the anaerobic digestion facilities. In addition, volatile acid/alkalinity ratio has been used to monitor the performance of anaerobic digestion process [24] and further study of volatile acid/alkalinity ratio as well as other parameters should be considered. Additionally further study of volatile fatty acids in comparison with microbial community is necessary to understand the microbial activities in terms of the series of reactions involved.

4. Conclusions

In Korea, there is lack of information on the field data for operation of anaerobic digestion facilities treating food waste leachate, especially for operational parameter for checklist of troubleshooting. This study evaluated the effect of volatile fatty acid concentration on volatile solid removal rate and investigated the relationship between them. The volatile solid removal rates of field anaerobic digestion facilities with food waste leachate were evaluated and the average volatile solid removal rates were below the Korean guideline of 65%. In order to meet the Korean guideline of 65% volatile solid removal rate, volatile fatty acid concentrations should remain below 4,000 mg/L on the field anaerobic digestion facilities treating FWL. Volatile fatty acid concentrations should be used as an important operational parameter to control and manage the anaerobic digestion process.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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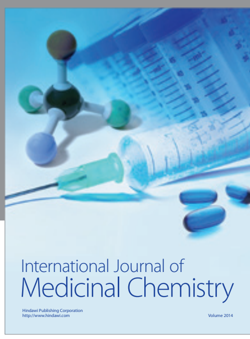
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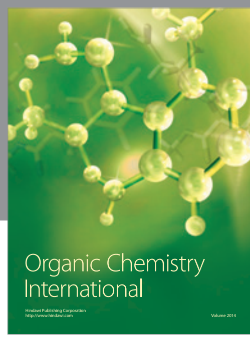
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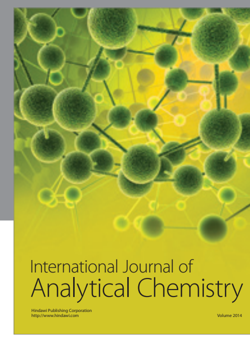
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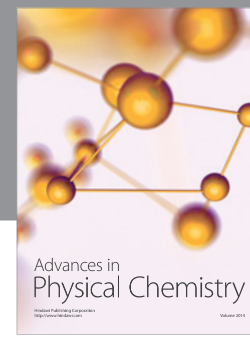
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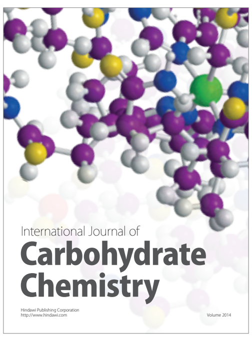
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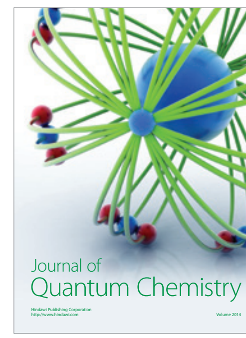
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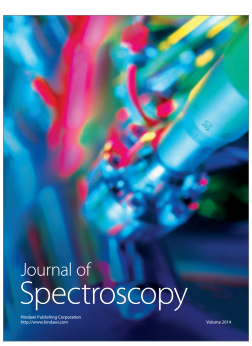
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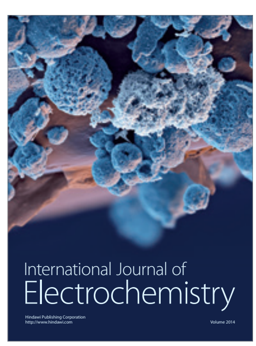
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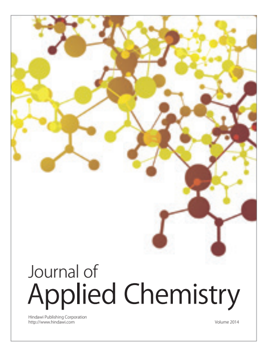
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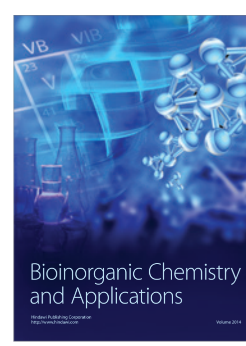
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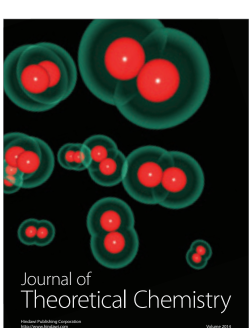
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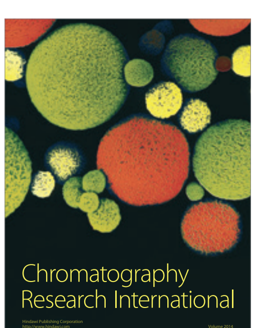
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