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Feasibility assessment of thermophilic anaerobic digestion process of food waste

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Abstract In this study, a lab-scale thermophilic anaerobic digestion of food waste collected from G-district in Seoul was performed to assess its feasibility and applicability in field-scale biogas plants. Monitoring parameters included biogas production, methane composition, pH, alkalinity, and volatile fatty acid (VFA) concentrations. Accumulation of VFA caused successive depression in pH, which inhibited microbial activity of methane-forming microorganisms. Signals of biological instability and inhibition of methanogenesis suggest possible process failure, as indicated by reduction in methane production. Results revealed that modifications in certain conditions, such as decreased organic loading rate (OLR) or additional insertion of alkalinity, must be made for its application in industrial-scale biogas plants, and that thermophilic anaerobic digestion of food waste may not be feasible without any modification.

Keywords Anaerobic digestion · Food waste · Thermophilic

Introduction

More than 48,000 tons of municipal solid wastes (MSW) are produced in Korea each day with up to 93 % (by wt.) organic content [1]. MSW generated in Korea can be categorized into standard garbage bag disposal, food wastes, and recyclable materials. Due to the increase of source and on-site recycling and improved refuse-handling equipment, substantial fractions of the discarded paper fraction, metals, and glass are being recycled, resulting in the production of more organic-rich and less biotoxic biowaste [2]. As direct disposal of food wastes into the ocean has been prohibited in Korea ever since 2005, alternative disposal and treatment method is imperative.

For its high organic content, food waste is considered as an ideal subject for anaerobic digestion. Anaerobic digestion is known to offer numerous significant advantages, such as low sludge production, low energy requirement, and possible energy recovery [3]. In the anaerobic digestion process, complex organic materials are first hydrolyzed and fermented by anaerobic microorganisms into fatty acids. The fatty acids are then oxidized by β-oxidation to produce hydrogen (H_2) and acetate, which are finally converted into methane and carbon dioxide by methanogenic archaea [4]. Due to its value as a potential renewable energy source and high biodegradability, there is a growing interest in anaerobic digestion of biowaste [5].

Conventionally used anaerobic digestion process is under mesophilic condition, in which a steady state of degradation and stabilization of organic materials is maintained. Yet, it is known that thermophilic anaerobic digestion offers several advantages over conventional mesophilic anaerobic digestion including a high degree of waste stabilization, decreased detention time, improved solids–liquid separation, and increased destruction of viral and bacterial pathogens [6, 7]. In spite of these benefits, however, poor operational stability still prevents anaerobic digestion from being widely commercialized [8].

Application of thermophilic anaerobic digestion technique may be hindered by the presence of various inhibitors, and various possible causes may lead to process

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Fig. 1 Photographs of collected food waste and separated impurities

instability. The biological instability of the process may be caused by feeding problems, temperature variations, lack of necessary trace elements, and the presence of inhibitory or toxic substances. Therefore, this study was performed to assess the biological stability and determine its feasibility of lab-scale anaerobic digestion of food waste under thermophilic condition. Daily biogas yield of the substrate fresh matter and its methane content, daily changes in pH and alkalinity, and changes in VFA concentrations were analyzed to monitor the biological stability of the process.

Materials and methods

Substrate and inoculum preparation

Food waste was collected from a food waste transit center in G-district of Seoul. A total of four visits, each on a different day of the week, were made to the transit center to make the substrate more representative of the actual food waste generated in Seoul. Impurities from the collected food waste were removed manually and weighed before they were ground with a mixer (Fig. 1). Grinding was used as the sole method of pretreatment of the substrate. Ground substrate was mixed to apply homogeneity and was kept frozen for its future use as the substrate for thermophilic anaerobic digestion process.

Sewage sludge was collected from J-sewage treatment plant in Seoul and used as the inoculum for this study. Acquired inoculum was pre-treated using a sieve with a pore size of 500 μm for the purpose of removing soil particles. No additional alkalinity, or buffer, was introduced into the inoculum.

Substrate and inoculum characterization

Prepared substrate and inoculum were analyzed for their characterization. Proximate analysis was conducted to find moisture, volatile solids (VS), and fixed solids (FS) content. Analysis was performed according to the Korean standard wastes test method. Moisture content was measured by drying the substrate at 105 °C overnight. VS and FS contents were measured by burning the dried substrate in the furnace at 550 °C for 3 h. Each test was triplicated, and the average values of each content were recorded in percentage by wet weight (Table 1).

Measurement of pH and additional water quality analyses of the substrate and inoculum were also conducted. pH was measured using the Korean standard wastes test method for semisolid substance. 10 g of the substrate was stirred with 25 mL of distilled water and let sit for 30 min. Using a pH meter, pH of this solution was measured. Total nitrogen, total ammonia, total phosphorus, and total and soluble chemical oxygen demands (TCOD & SCOD) were measured using water quality analyzing kit products (Water Test Kit, Humas, Korea). Each product is based on standard wastes test method, EPA standard method, and AWWA standard method. Chromotropic acid was used as a reagent for measuring total nitrogen, Nessler method was used for measuring total ammonia, Molybdovanadate method was used for measuring total phosphorus, and COD_{Cr} was used for measuring total and soluble COD. A dilution factor of 200 (i.e., 1 mL of homogeneously mixed food waste was stirred with 199 mL of distilled water) was used for measuring COD. Soluble COD was obtained by extracting the soluble portion of the diluted food waste solution by vacuum filter and 0.45 μm syringe filter. Total nitrogen, total ammonia, and total phosphorus are presented in unit of mg per liter of substrate. Total COD and soluble COD are also presented in the unit of mg/L

Table 1 Proximate analysis of substrate and inoculum

	Substrate	Inoculum
Moisture (%, by wet wt.)	79.58	97.32
Ash (%, by wet wt.)	1.87	0.92
Volatile Solids (%, by wet wt.)	18.55	1.76

Table 2 Water quality analysis of substrate and inoculum

Item	Substrate	Inoculum
pH	5.15	7.27
Total Nitrogen (mg/L)	2820	2453
Total NH_3 (mg/L)	513	1337
Total Phosphorus (mg/L)	1881	–
TCOD (mg/L)	146,449	–
SCOD (mg/L)	71,063	–

Table 3 Heavy metal content of substrate

Item	Value (% DM)
K	1.82×10^{-2}
Zn	5.45×10^{-5}
Cu	N.D.
Ni	N.D.
Pb	N.D.
Cd	N.D.
Cr	N.D.

DM dry matter, *N.D.* not detected

(Table 2), which indicates mass of oxygen consumed per liter of solution.

Heavy metal concentrations of prepared substrate were analyzed with an ICP-OES spectrometer (iCAP 7400, Thermo, USA). Mixed food waste was oven-dried and was pre-treated using a microwave digester according to the EPA 3052 method for heavy metal analysis. Heavy metals of interest included K, Zn, Cu, Ni, Pb, Cd, and Cr. Each test was performed in triplicate and the average values were recorded (Table 3).

Reactor operation and monitoring

Two continuous stirred-tank reactors (CSTR) with an effective volume of 8 L were used in this study as a duplicate. Temperature control of each reactor was achieved by applying an outer layer that serves as a water jacket and a water bath that could circulate heated water within the water jacket. Both reactors were set under thermophilic condition with their temperature controlled at 50 °C. Anaerobic condition was achieved by purging each reactor with nitrogen gas before the digestion process. To allow some acclimation period to the anaerobic microorganisms within each reactor, gradual and careful changes in the environment were employed. The organic loading rate (OLR) of both reactors was to start off as 0.5 g organic dry matter (ODM)/L/day with a 10 % increment in OLR each day until it reaches 4.0 g ODM/L/day. Our previous study had indicated no complication with this OLR increment under mesophilic condition. Thermophilic anaerobic digestion process is known for its advantage in reducing the retention time, thus upholding such operating condition feasible. A pulse feeding method was used using a syringe, and the prepared substrate was fed two times a day. Consistent stirring with constant RPM was managed using an electrical motor attached to each reactor.

Once both reactors were set and daily feeding had started, biological stability within each reactor was monitored. Produced biogas composition was measured daily using gas chromatography (ACME 6100, Younglin, Korea) equipped with a thermal conductivity detector (TCD), and helium gas was used as the carrier gas. Using gas chromatography, the composition of produced biogas (i.e., methane, carbon dioxide, and nitrogen) was determined in the fraction of total volume of the daily biogas yield. Occasional organic volatile acid concentration was also measured using gas chromatography equipped with a flame ionization detector (FID). Helium, hydrogen, and air was used as the carrier gas with the main volatile fatty acids (VFA) of interest being acetic acid, propionic acid, butyric acid, isobutyric acid, valeric acid, isovaleric acid, and hexanoic acid.

Alkalinity and pH of the daily effluent were monitored. The methods of Jenkins et al. [9] and Ripley et al. [10] were used for quantifying the alkalinity. Following centrifugation of the effluent, the supernatant was titrated with standardized 0.02 N sulfuric acid to an endpoint of pH 5.7 and pH 4.3. The titration method outlined in "Standard Methods for the Examination of Water and Wastewater" [11] was utilized and the alkalinity was calculated using the following equation:

$$\text{Alkalinity, mg } CaCo_3/L = \frac{A \times N \times 50,000}{\text{mL sample}} \quad (1)$$

where: $A =$ mL standard acid used $N =$ normality of standard acid.

Volume of standardized sulfuric acid used to an endpoint of pH 5.7 and pH 4.3 was used to calculate partial alkalinity (PA) and total alkalinity (TA), respectively. Intermediate alkalinity (IA) was calculated as the difference between PA and TA.

Results and discussion

Biogas yield and methane composition

Anaerobic digestion process yields biogas such as methane, carbon dioxide, nitrogen, and some traces of ammonia nitrogen and hydrogen sulfide. Among many other final products of anaerobic digestion, methane production is not

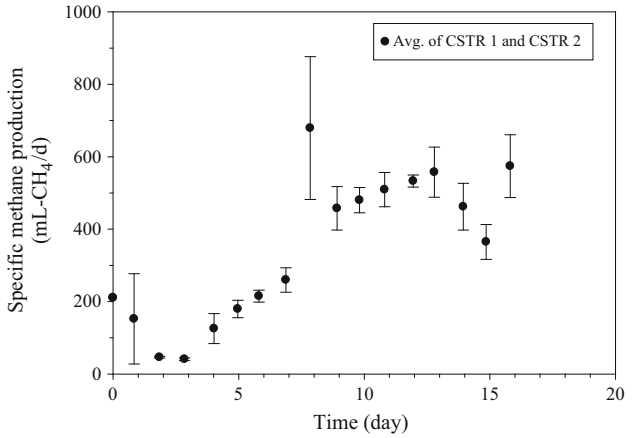

Fig. 2 Specific methane production of CSTR 1 and CSTR 2. *Error bars* represent standard deviations

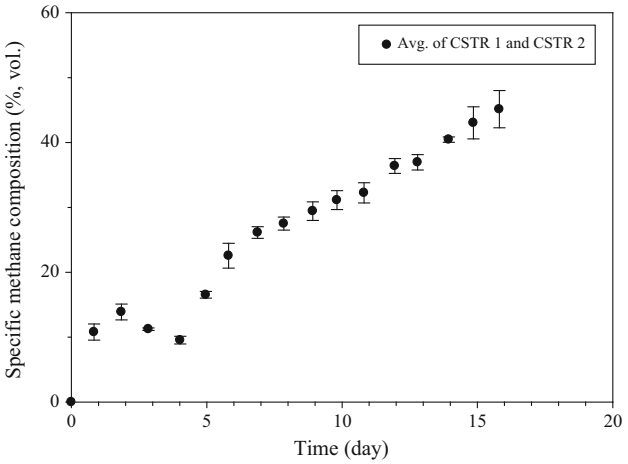

Fig. 3 Specific methane composition of CSTR 1 and CSTR 2. *Error bars* represent standard deviations

only of most interest, but also one of the most important parameters to monitor in the process. This is because process instability is usually indicated by a rapid increase in the concentration of volatile acids with a subsequent decrease in methane gas production [12]. With constant OLR, reasonably stable biogas production can be expected. Figure 2 illustrates the specific production of methane gas in each reactor during the operation. The figure shows an increasing trend in methane gas production until the first 12–13 days, but a sharp decrease can be witnessed afterwards. As decomposed organic matter is converted into methane gas, daily increase in OLR was anticipated to result in increase in daily methane gas production. Until the first 12–13 days of reactor operation, increasing trend in methane production was concurrent to the daily increment in OLR. However, successive drastic decrease in methane production despite the increased OLR may suggest process instability.

Methane gas composition also serves as one of the major monitoring parameters when operating anaerobic digestion. Fairly stable methane content within the optimal range must be maintained when constant amount of substrate is fed into the reactor. Figure 3 illustrates the specific composition of methane gas produced in each reactor during the operation. The figure shows an increasing trend in methane composition with its maximum composition as high as 48.01 % by volume in CSTR 2.

pH and alkalinity

Efficient anaerobic digestion process requires maintenance of pH as microbial activity can be easily inhibited by low pH. Generally accepted optimal pH values are within the neutral pH range [13]. Figure 4 shows the pH change within each reactor. Initial pH of both reactors was around

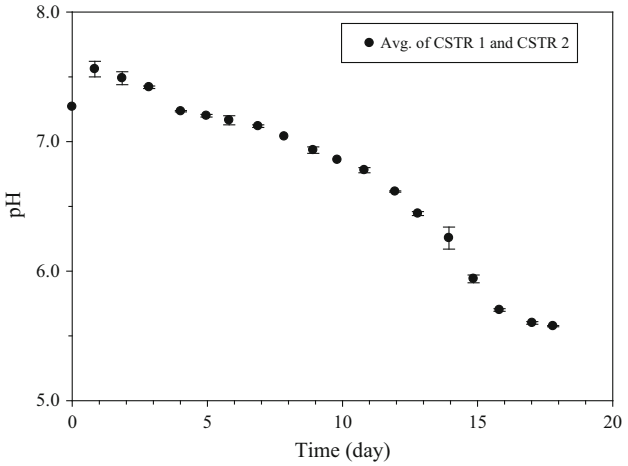

Fig. 4 pH change within CSTR 1 and CSTR 2. *Error bars* represent standard deviations

7.5, indicating an optimal neutral pH level. Yet, the pH in both reactors started to drop significantly as daily feeding of food waste continued. It is known that the optimal pH for methanogenesis is around 7.0 [14]. Drastic decrease in pH may have caused microbial inactivity of methanogenic archaea and subsequent inhibition of methanogenesis. Reduction in pH suggests an accumulation of VFAs and a successive imbalance between acid producers and consumers [15, 16].

Alkalinity is directly related to pH in that alkalinity is the ability of a solution to neutralize acids. In anaerobic digestion, alkalinity provides buffering capacity to withstand moderate shock loads of VFA. Therefore, changes in concentrations of VFAs and alkalinity also become major monitoring parameters of anaerobic digestion process. The ratio between intermediate alkalinity (IA) and partial

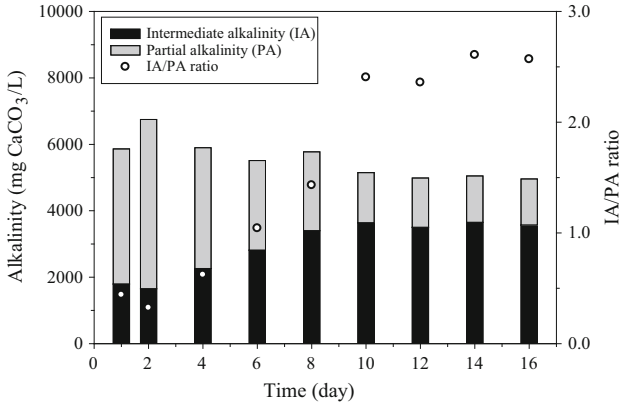

Fig. 5 Change in alkalinity and IA/PA ratio within CSTR 1 and CSTR 2

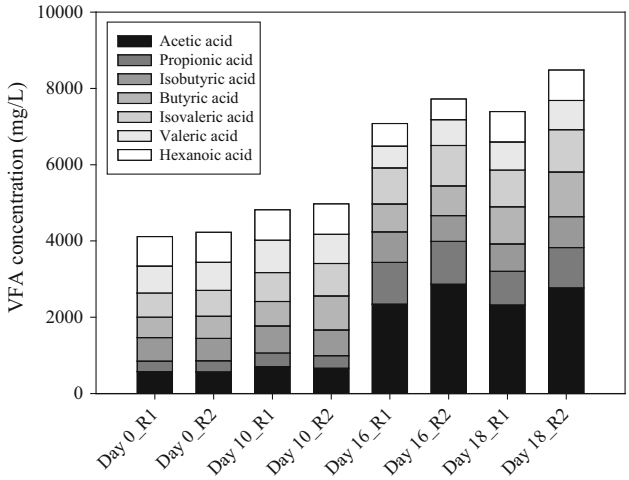

Fig. 6 VFA concentration within R1 (CSTR 1) and R2 (CSTR 2)

alkalinity (PA), or also known as the IA/PA ratio, is usually utilized as an indicator of process stability. Intermediate alkalinity represents the accumulation of volatile fatty acids, whereas partial alkalinity indicates the bicarbonate buffer capacity [17]. IA/PA values above 0.3 for domestic sewage had indicated disturbances in anaerobic digestion according to Ripley et al. [10], but Pereira et al. [18] stated that process stability may be achieved even with IA/PA values different from 0.3 due to variations in effluent characteristics. Although the optimal alkalinity ratio may be different between biogas plants depending on various feedstocks or pretreatment methods [19], process stability is usually indicated by maintenance of fairly stable IA/PA ratio throughout the process. However, constant increase in IA/PA ratio within both reactors was observed in this study (Fig. 5). Rapid increase in IA/PA ratio indicates accumulation of volatile fatty acids along with some consumption of alkalinity. Depression of pH in this study may have resulted from accumulation of volatile fatty acids exceeding the buffering capacity, thus inhibiting the activity of microorganisms which can degrade volatile acids and subsequently ceasing methane production.

Volatile fatty acids (VFA)

Reactor acidification due to accumulation of volatile fatty acids is one of the most common reasons for inhibitory effects on microorganisms and subsequent process deterioration in anaerobic digesters [20, 21]. Thus, periodic monitoring of VFA concentrations is necessary when determining biological stability of anaerobic digestion process. Build-up of acetic acid in excess of 800 mg/L can explain process inhibition, and accumulation of propionic acid concentration of 900 mg/L is known to be an indicator of failure of methanogenesis [16, 22, 23]. Figure 6 illustrates the concentration of accumulated VFA within each reactor during reactor operation. Total concentration of VFA did not exceed 5000 mg/L in both reactors with acetic acid and propionic acid less than 800 and 900 mg/L, respectively, until the 10th day of reactor operation. Nonetheless, continuous accumulation of VFA led to an increased total VFA concentration up to 8482 mg/L in CSTR 2. Concentrations of both acetic acid and propionic acid in both reactors also showed drastic increases with their values exceeding 2000 and 1000 mg/L, respectively, suggesting an impending digester failure. It is known that each anaerobic digestion plant has a different optimal concentration of VFA corresponding to the characteristics of the substrate [24]. However, drastic increase in total VFA concentration may suggest inhibition of methanogenesis along with accelerated degradation of organics and successive acid production.

Conclusion

Although thermophilic anaerobic digestion may sound attractive as it may yield larger quantities of methane gas, this may be an inadequate consideration due to excessively accelerated decomposition of organics. Accelerating decomposition and hydrolysis of food waste, which is an already easily biodegradable matter, may cause organic overload, resulting in accumulation of volatile fatty acids and subsequent reduction in pH. Such pH depression inhibits activity of methanogenic archaea and causes possible reactor failure, as indicated by reduced biogas production. In sum, the imbalance between the activities of acid-forming and methane-forming microorganisms has been the primary cause of process instability. As these two groups of microorganisms differ widely in terms of physiology, nutritional needs, growth kinetics, and sensitivity to

environmental conditions, maintenance of balance between the two is essential in anaerobic digestion. Further research on reaction kinetics of anaerobic microorganisms is required for better understanding of thermophilic anaerobic digestion process. Results of this study revealed that modifications in certain conditions, such as decreased organic loading rate or additional insertion of alkalinity, must be made for its application in industrial-scale biogas plants.

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