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Simulation on Long-term Operation of an Anaerobic Bioreactor for Korean Food Wastes

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Abstract A mathematical model was formulated to simulate the long-term performance of an anaerobic bioreactor designed to digest Korean food wastes. The system variables of various decomposition steps were built into the model, which predicts the temporal characters of solid waste, and volatile fatty acid (VFA) in the reactor, and gas production in response to various input loadings and temperatures. The predicted values of VFA and gas production were found to be in good agreement with experimental observations in batch and repeated-input systems. Finally, long-term reactor performance was simulated with respect to the seasonal temperature changes from 5°C in winter to 25°C in summer at different food waste input loadings. The simulation results provided us with information concerning the success or failure of a process during long-term operation.

Keywords: mathematical model, anaerobic digestion, food wastes, volatile fatty acids, methane

INTRODUCTION

Food waste causes serious environmental problems in Korea not only because of the fact that Koreans dispose of three times more per capita than the Americans and the Japanese, but also because of the lack of proper treatment methods. These food wastes amount to 4.1 million tons (wet)/year 2002 and is claimed to be worth 15 Jo-won (equivalent to 12.5 billion US$)[1].

Landfill was the primary choice for handling these wastes but has now been banned because of the exhaustion of existing landfill sites, moreover, it is difficult to find new sites and the leachate generated by these materials requires secondary wastewater treatments [2]. The incineration of food waste is unsuitable because of its high water content and the possibility of dioxin generation. Composting into fertilizer and converting the material to animal feed have been practiced as ways of treating large amounts of the food wastes, but large amounts of wastewater are generated when desalting the food wastes for fertilizer production, and animal feeds produced from this material often creates hygiene problems for feeding animals. Clearly, we are running out of available options, leaving only one clear alternative, the aerobic or anaerobic digestion of food wastes [3]. These methods have their pros and cons, but in the present study, we considered the anaerobic method because energy can be recovered in the form of methane and it generally requires less energy than the aerobic alternative [4].

Anaerobic digestion is a complex multistage process of converting organic compounds to methane and carbon dioxide by utilizing the activities of numerous anaerobic microorganisms. Although the process has been well studied, its kinetic irregularities and the interactions between different generic groups of bacterial within an anaerobic ecosystem are not well understood. There is a need for a dynamic model capable of analyzing the process operation on a quantitative basis. This would lead ultimately to the development of better control procedures, which would prevent process failures and optimize process performance. A dynamic model would also be valuable for improving process design since it would allow comparisons of different processing options with respect to process stability. This growing interest during the past years has resulted in the development of a variety of mathematical models for different anaerobic digestion processes [5-11]. However, little progress has been made on mathematical model dealing with food wastes as substrates.

Methane production from Korean food waste was investigated to allow the design of a suitable model for the stable operation of an anaerobic digester by considering food waste decomposition into organic monomers, organic acids such as acetic, propionic and butyric acids, and methane formation. The simulation results from the seasonal model describe the behavior of an anaerobic digester during a yearlong operation with and without temperature control. A proper input strategy in the case of a no temperature control policy will also be proposed for the stable operation of a digester.

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Table 1. Elemental compositions, total solid, and volatile solid contents of Korean food waste samples (dwb = dry weight basis)

	C (%,dwb)	H (%,dwb)	O (%,dwb)	N (%,dwb)	TS (%,w/w)	VS (%,w/w)
1	46.0931	6.4023	38.1492	2.8544	19.1	18.3
2	46.0690	6.6340	39.7443	3.9519	20.9	19.8
3	48.9324	7.2343	38.4180	3.9953	21.1	20.0
4	47.3507	7.0719	42.1748	2.4478	13.6	13.3
5	47.9672	7.2542	40.1857	4.3271	19.6	18.6
Mixture	48.1521	7.2036	39.2630	3.9330	18.9	17.9

TS, VS basis = 1kg of wet foodwaste; C, H, O, N basis = 1 kg of dry foodwaste.

MATERIALS AND METHODS

Microorganisms

The microorganisms used in this study were components of anaerobic digestion sludge from Daejeon Sanitary Treatment Plant in Daejeon, Korea. The sludge was acclimated with about 2-3 g volatile solids (VS) /L of ground food wastes at 35°C for a month.

Food Waste

Food waste samples were collected on five occasions from the cafeteria at KAIST. The samples were mixed and chopped, and stored at -20°C. Table 1 shows the elemental compositions, total solids (TS), and VS contents of the Korean food waste samples used in this study. A mixture of these samples is described as the standard sample in this study.

Experimental Setup and Operation

The sludge was dispensed into flasks (270 mL actual volume; stopped with a 2-cm thick silicone rubber bung) under O_2 free N_2 gas. Each flask contained a 200 mL - mixture of sludge and food waste. A set of digesters that contained no food waste served as the control. The temperature of all the digesters was maintained at 35°C and these were agitated twice a day.

Analytical Procedures

Gas volume was determined by measuring the volume of gas given off by using water-level changes in gas volume measuring equipment (Fig. 1). The composition of the gas produced was determined by gas chromatography (Varian 3300, USA) equipped with a packed column (Silica gel, 4 m, 40/60 mesh; Davison Grade, USA) and a TCD detector using helium as the carrier gas. Individual VFA concentrations were determined using a HPLC unit (Hitachi L-3300 RI monitor, L-6000 pump, D-2500 chromate-integrator, Tokyo, Japan) equipped with an ion-exchange column (Amine HPX-87H, 300 × 7.8 mm; Bio-Rad, Hercules, CA, USA) and using a 0.01N H_2SO_4 mobile phase. Sample pH's were determined with a meter (Hanna HI1230, Italy), and the TS and VS of samples were determined using standard methods [12]. Elemental compositions of the samples were determined using an elemental analyzer (Profile HV-3, Germany).

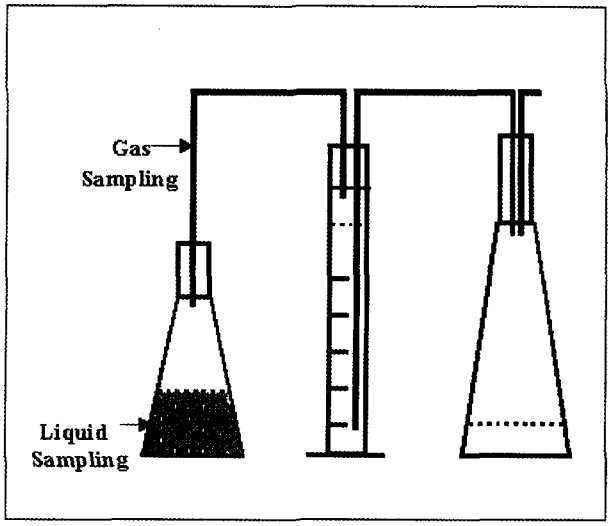

Fig. 1. Schematic diagram of gas measuring device in an anaerobic digestion system.

MODEL DEVELOPMENT

Outline of the Model

A schematic of our proposed model for the anaerobic digestion of Korean food waste is shown in Fig. 2 [13]. The model involves five bacterial groups: organic monomer-degrading acidogens (X_1), propionate-degrading acidogens (X_2), butyrate-degrading acidogens (X_3), acetoclastic methanogens (X_4), and hydrogenotrophic methanogens (X_5).

Hydrogen inhibition in the acidogenic step is considered because of the activity of the acidogenic bacteria [6]. Also hydrogen inhibition in the acetogenic step has been included to account for the blockade of this reaction at high hydrogen partial pressures [10,11]. In addition to the hydrogen inhibition, acetate inhibition of the butyrate-degrading step [14] and inhibitions caused by intermediary products, such as propionate and butyrate, on the methanogenic step [10,11] are also considered.

Bacterial decay has been included in the model because the experiments were carried out over an extended time [10,11].

Stoichiometry

In the following bacterial steps, cell mass is represented by the empirical formula $C_5H_9O_3N$ [6]. To obtain the

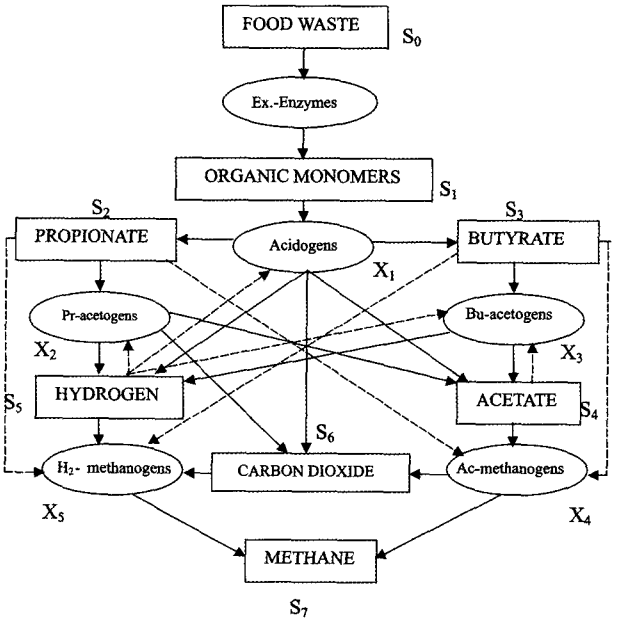

Fig. 2. Outline of the model (——material flow, ------inhibition). organic monomers (S_1) and their-degrading acidogens (X_1), propionate (S_2) and its-degrading acidogens (X_2), butyrate(S_3) and its degrading acidogens (X_3), acetic acids (S_4) and aceto-clastic methanogens (X_4), hydrogen (S_5) and hydrogenotro-phic methanogens (X_5).Carbon dioxide (S_6) and Methane (S_7). Sample explanation: organic monomers (S_1) are decomposed by acetogens groups (X_1) into S_4, S_2, S_3, S_5 and S_6. These reactions are inhibited by hydrogen, S_5.

stoichiometric ratio for the products of organic monomer degradation, the bacterial activity in the acetogenic and methanogenic steps were suppressed by performing the experiments at below pH 5.0. It was assumed that organic polymers are converted into monomers by extracellular enzymes obeying first-order kinetics.

The stoichiometry of each step is described as follows [15]:

Acidogenesis

$$C_{4.02}H_{7.20}O_{2.46}N_{0.28} + 1.42H_2O \longrightarrow 0.57C_2H_4O_2 + 0.32C_3H_6O_2 + 0.29C_4H_8O_2 + 1.34H_2 + 0.76CO_2 + 0.28NH_3 \quad (1)$$

$$C_{4.02}H_{7.20}O_{2.46}N_{0.28} + 0.524NH_3 \longrightarrow 0.804C_5H_9O_3N + 0.72H_2 + 0.048H_2O \quad (2)$$

Propionate acetogenesis

$$C_2H_5COOH + 2H_2O \longrightarrow CH_3COOH + CO_2 + 3H_2 \quad (3)$$

$$C_2H_5COOH + 0.6NH_3 \longrightarrow 0.6C_5H_9O_3N + H_2 + 0.2H_2O \quad (4)$$

Butyrate acetogenesis

$$C_3H_7COOH + 2H_2O \longrightarrow 2CH_3COOH + 2H_2 \quad (5)$$

Table 2. Specific growth rates [17].

$$\mu_1 = \frac{\mu_{m,1} \cdot S_1}{K_{s,1} + S_1} \cdot \frac{1}{1 + S_5 / K_{I,1}}$$

$$\mu_2 = \frac{\mu_{m,2} \cdot S_2}{K_{s,2} + S_2} \cdot \frac{1}{1 + S_5 / K_{I,2}}$$

$$\mu_3 = \frac{\mu_{m,3} \cdot S_3}{K_{s,3} + (1 + S_4 / K_{I,3}) + S_3} \cdot \frac{1}{1 + S_5 / K_{I,4}}$$

$$\mu_4 = \frac{\mu_{m,4} \cdot S_4}{K_{s,4} + S_4} \cdot \frac{1}{1 + S_2 / K_{I,5}} \cdot \frac{1}{1 + S_3 / K_{I,6}}$$

$$\mu_5 = \frac{\mu_{m,5} \cdot S_5 \cdot S_6}{(K_{s,5} + S_5)(K_{s,6} + S_6)} \cdot \frac{1}{1 + S_2 / K_{I,7}} \cdot \frac{1}{1 + S_3 / K_{I,8}}$$

$$C_3H_7COOH + 0.8NH_3 + 0.4H_2O \longrightarrow 0.8C_5H_9O_3N + 2H_2 \quad (6)$$

Acetoclastic methanogenesis

$$CH_3COOH \longrightarrow CH_4 + CO_2 \quad (7)$$

$$CH_3COOH + 0.4NH_3 \longrightarrow 0.4C_5H_9O_3N + 0.8H_2O \quad (8)$$

Hydrogenotrophic methanogenesis

$$H_2 + 0.25CO_2 \longrightarrow 0.25CH_4 + 0.5H_2O \quad (9)$$

$$H_2 + 0.5CO_2 + 0.1NH_3 \longrightarrow 0.1C_5H_9O_3N + 0.7H_2O \quad (10)$$

Growth Kinetics and Material Balances

The bacterial growth kinetics is based on the assumption that the growth of biomass proceeds according to Monod kinetics in the presence of inhibition by some process components [16]. A general equation for the specific bacterial growth rate can be written as

$$\mu_j = \frac{\mu_{m,j} \cdot S_j}{F(I_g) \cdot (K_{s,j} \cdot F(I_{g'}) + S_j)} \quad (11)$$

where $F(I_g)$ and $F(I_{g'})$ are noncompetitive and competitive inhibition functions respectively [11]. Acetate inhibition of the butyrate-degrading step is approximated by competitive inhibition function as reported by Denac [17]. All other inhibitions proceed according to noncompetitive kinetics [6].

The specific growth rates used here are presented in Table 2 and material balances are shown in Tables 3 and 4 [6,17]. All product formations are directly coupled to biomass production due to the dissimilar rates of anaerobic digestion. Substrate consumption for maintenance is incorporated in the overall biomass yield and bacterial decay is described by first-order kinetics [6].

Gas Concentration and Transport

The anaerobic bioreactor consists of gas phase and

Table 3. Material balances for bacterial groups

$$\frac{dX_1}{dt} = \mu_1 \cdot X_1 - b_1 \cdot X_1$$

$$\frac{dX_2}{dt} = \mu_2 \cdot X_2 - b_2 \cdot X_2$$

$$\frac{dX_3}{dt} = \mu_3 \cdot X_3 - b_3 \cdot X_3$$

$$\frac{dX_4}{dt} = \mu_4 \cdot X_4 - b_4 \cdot X_4$$

$$\frac{dX_5}{dt} = \mu_5 \cdot X_5 - b_5 \cdot X_5$$

Table 4. Material balances [17]

$$\frac{dS_0}{dt} = -k \cdot S_0$$

$$\frac{dS_1}{dt} = -\frac{\mu_1}{Y_1} \cdot X_1 + k \cdot S_0$$

$$\frac{dS_2}{dt} = 0.32 \cdot (1 - f_1 \cdot Y_1) \cdot \frac{\mu_1}{Y_1} \cdot X_1 - \frac{\mu_2}{Y_2} \cdot X_2$$

$$\frac{dS_3}{dt} = 0.29 \cdot (1 - f_1 \cdot Y_1) \cdot \frac{\mu_1}{Y_1} \cdot X_1 - \frac{\mu_3}{Y_3} \cdot X_2$$

$$\frac{dS_4}{dt} = 0.57 \cdot (1 - f_1 \cdot Y_1) \cdot \frac{\mu_1}{Y_1} \cdot X_1 + (1 - f_2 \cdot Y_2) \cdot \frac{\mu_2}{Y_2} \cdot X_2 + 2 \cdot (1 - f_3 \cdot Y_3) \cdot \frac{\mu_3}{Y_3} \cdot X_3 - \frac{\mu_4}{Y_4} \cdot X_4$$

$$\frac{dS_5}{dt} = 1.24 \cdot (1 - f_1 \cdot Y_1) \cdot \frac{\mu_1}{Y_1} \cdot X_1 + 3 \cdot (1 - f_2 \cdot Y_2) \cdot \frac{\mu_2}{Y_2} \cdot X_2 + 2 \cdot (1 - f_3 \cdot Y_3) \cdot \frac{\mu_3}{Y_3} \cdot X_3 - \frac{\mu_5}{Y_5} \cdot X_5$$

$$\frac{dS_6}{dt} = 0.76 \cdot (1 - f_1 \cdot Y_1) \cdot \frac{\mu_1}{Y_1} \cdot X_1 + (1 - f_2 \cdot Y_2) \cdot \frac{\mu_2}{Y_2} \cdot X_2 + (1 - f_4 \cdot Y_4) \cdot \frac{\mu_4}{Y_4} \cdot X_4 - 0.25 \cdot (1 - f_5 \cdot Y_5) \cdot \frac{\mu_5}{Y_5} \cdot X_5 - 0.5 \cdot f_5 \cdot \mu_5 \cdot X_5$$

$$\frac{dS_7}{dt} = (1 - f_4 \cdot Y_4) \cdot \frac{\mu_4}{Y_4} \cdot X_4 + 0.25 \cdot (1 - f_5 \cdot Y_5) \cdot \frac{\mu_5}{Y_5} \cdot X_5$$

the solid/liquid slurry phase in which the reaction takes place due to acclimated sludge. It is assumed that each phase is completely mixed and homogeneous. Gases generated in the solid/liquid phase, such as H_2, CH_4, and CO_2, move into the gas phase but maintain equilibrium between the two phases. The pressure of the gas phase is maintained at slightly over 1 atmosphere, so that the gases produced vented from the reactor.

Gas concentrations are obtained by developing material balances for each gas in both phases, and by considering interphase transfer. The equations are as follows:

solid/liquid phase (for i = H_2, CO_2, CH_4)

$$\frac{dS_i'}{dt} = \frac{dS_i}{dt} + K_L a_i \cdot (S_i^{Eq} - S_i') \quad (12)$$

Table 5. Growth and inhibition parameters

Bacterial groups	μ_m (h^{-1})	K_s (mM)	$K_{I,H2}$ (mM)	$K_{I,Ac}$ (mM)	$K_{I,Pr}$ (mM)	$K_{I,Bu}$ (mM)	b (h^{-1})	Y (g/mM)
X_1	0.175	0.128	0.0321				0.00313	0.00022
X_2	0.009	1.100	0.3205				0.00313	0.00020
X_3	0.011	1.100	0.0036	10			0.00125	0.00045
X_4	0.015	2.300			35	21	0.00783	0.00025
X_5	0.058	0.008 0.010			29	16	0.00313	0.00004

Table 6. Conversion factors [17]

Conversion factor	$C_{4.02}H_{7.20}O_{2.46}N_{0.28}$	C_2H_5COOH	C_3H_7COOH	CH_3COOH	H_2
f	10.1	13.5	11.4	16.7	500

Sample explanation: f_1 means a simple conversion factor of monomer "g" to monomer "mM" while Y_1 means "gram cell" per "mM" of substrate. $(1\text{-}f_1Y_1)$ represents the sum of organic monomer fraction that can be converted to S_2, S_3, S_4, S_5 and S_6.

gas phase (for i = H_2, CO_2, CH_4)

$$V_g \frac{dS_i^*}{dt} = -V_L \cdot K_L a_i \cdot (S_i^{Eq} - S_i') - Q \cdot S_i^* \quad (13)$$

Computational Method

Simulations were performed by integrating the relevant equations using MATLAB 5.1 (The MathWorks. Inc.). Results were obtained as an output data file in a format suitable for graphic processing.

Model Parameters and Other Conditions

Many preliminary simulations were performed to determine the most appropriate set of model parameters. The values of the model parameters were chosen to be in ranges consistent with the present study or were taken from the literature [11]. Table 5 shows the growth and inhibition parameters used in this study. Tables 6, 7, and 8 show conversion factors, Henry's law constants and mass transfer coefficients for gases, and the initial conditions used for the different bacterial groups, respectively [15]. The initial conditions of all intermediate and final products were set to zero in both phases. The first-order specific growth rate for the hydrolysis of organic polymers at 35°C was taken to be 0.05 h^{-1}. The volume of the gas phase was 70 mL and that of solid/liquid phase 200 mL. The pressure of the system was maintained at slightly over 1 atm.

The first-order specific growth rates and other kinetic parameters at 25, 15, and 5°C are presented in Table 9. The parameters at 25°C and 15°C were obtained by experiment (Fig. 5). Parameters at 5°C were estimated

Table 7. Henry's law constants and mass transfer coefficients for gases [15]

	H_2	CO_2	CH_4
H (atm/mol fraction)	74,000	21,000	48,500
K_La (h^{-1})	4.17	4.17	4.17

Table 8. Initial conditions of bacterial groups (assumed)

Bacterial group	X_1	X_2	X_3	X_4	X_5
Concentration (g/L)	0.0550	0.0125	0.0800	0.0440	0.0240

Table 9. The first-order kinetic parameter and specific growth rates at various temperature

Temperature (°C)	k (h^{-1})	μ_1 (h^{-1})	μ_2 (h^{-1})	μ_3 (h^{-1})	μ_4 (h^{-1})	μ_5 (h^{-1})
35	0.050	0.175	0.0090	0.0110	0.0150	0.058
25	0.017	0.108	0.0055	0.0070	0.0062	0.030
15	0.008	0.040	0.0016	0.0022	0.0018	0.015
5	0.004	0.015	0.0005	0.0007	0.0005	0.007

using the van't Hoff-Arrhenius relationship.

$$k_T = k_{25} \cdot \theta^{(T-25)} \quad (14)$$

The θ values for other bacterial groups were shown in Table 10 [18].

RESULTS AND DISCUSSION

Anaerobic Digestion of Korean Food Waste in a Batch System

Anaerobic digestion of food waste was carried out in a single input process. The initial food waste concentration was 5 g VS/L and the initial pH of the medium was set at 7.90, because this was the optimum initial pH for methane production (data not shown). The simulation results demonstrated the characteristics of the anaerobic digestion of Korean food waste in terms of cumulative gas production (Fig. 3). Also Fig. 3 shows that most of the gas production occurred within 2 days from the start of the digestion. The model slightly overestimated cumulative gas production, which was attributed to losses during sampling, but the model predicted the production rate fairly well.

Fig. 4 shows the VFA, food waste and organic monomer concentrations in the digester. Simulation showed that organic monomer concentrations were extremely low. The maximum organic monomer concentration was

Table 10. The θ values of van't Hoff-Arrhenius relationship [18]

θ_k	$\theta_{\mu1}$	$\theta_{\mu2}$	$\theta_{\mu3}$	$\theta_{\mu4}$	$\theta_{\mu5}$
1.078	1.104	1.131	1.123	1.132	1.072

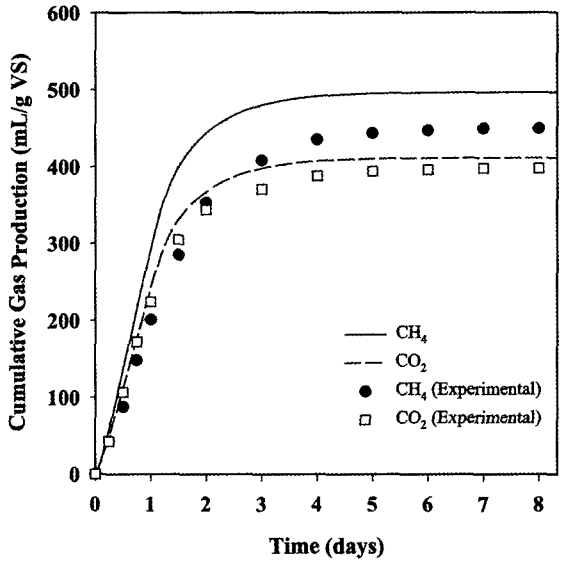

Fig. 3. Model prediction versus observed values of cumulative gas production at 5 g VS/L of initial food waste (Initial pH = 7.90, Temperature = 35°C).

0.00082 g/L when the food waste concentration was 5 g VS/L. Since the acidification rate of organic monomers was relatively high, only low levels of organic monomer were present in the digester. This relationship means that the rate limiting steps of the process are hydrolysis and methane formation. The model also predicted the time history of VFA concentrations well. All kinds of VFA concentrations reached a maximum after 12 h. Maximum concentrations of acetic, propionic, and butyric acids were 0.55, 0.20, and 0.10 g/L, respectively. VFAs were nearly exhausted 2 days from the beginning of the digestion, which is why most gas was produced within 2 days, as shown in Fig. 3. It is evident that the overall gas production rate was controlled by the hydrolysis rate after 2 days.

Temperature Effect on VFA Concentrations

It is generally reported that the optimum temperature of a mesophilic anaerobic digestion system is 35°C [19]. Figure 5 shows the VFA concentrations at 25 and 15°C from which the model parameters were derived. The exhaustion time of VFA increased as the temperature decreased: 2 days at 35°C, 5 and 16 days at 25 and 15°C, respectively. The maximum acetic acid concentration was twice as high as that of other acids at 15°C, which means that acetate-degrading methanogens are

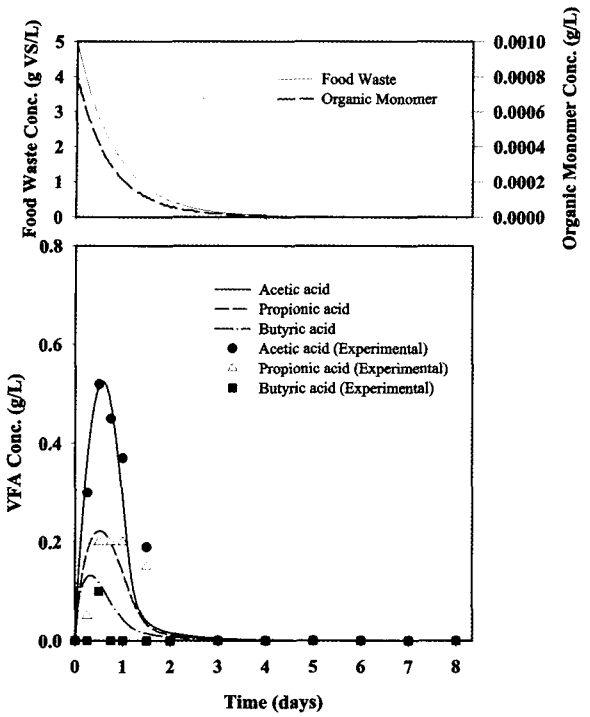

Fig. 4. Model prediction versus observed values of VFA concentration and its predicted solid food waste consumption and organic monomer concentration at an initial food waste level of 5 g VS/L (Initial pH = 7.90, Temperature = 35°C).

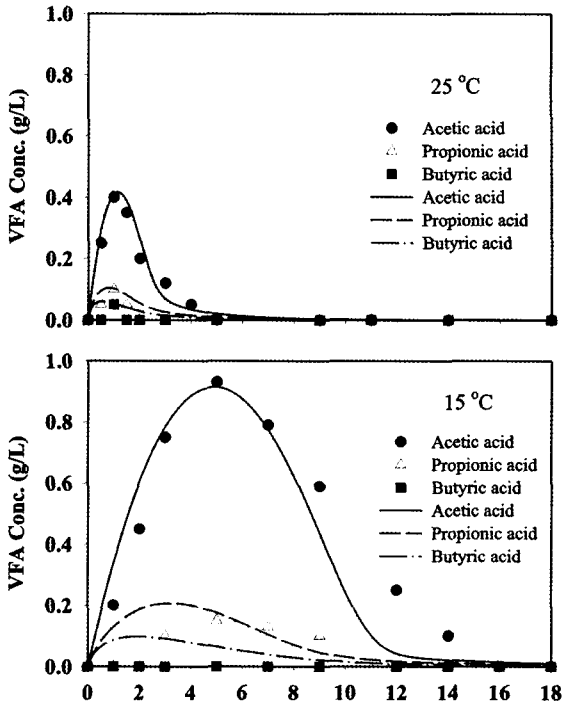

Fig. 5. VFA concentrations at various temperature 15, 25°C.

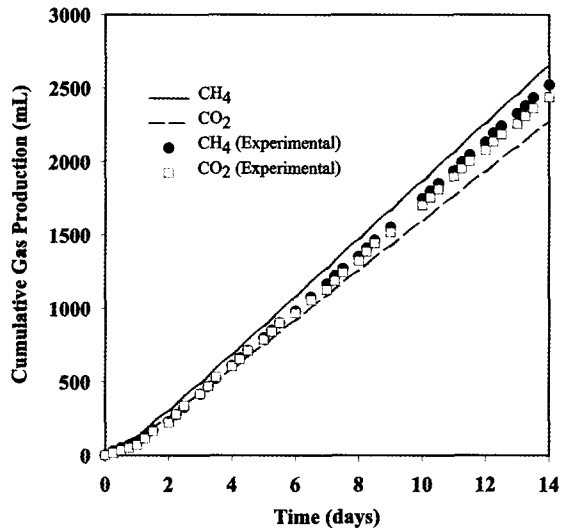

Fig. 6. Model prediction versus observed values of cumulative gas production in a repeated input operation at 2 g VS L^{-1} day^{-1} (Temperature = 35°C).

more sensitive to temperature than other group of microorganisms. In order to prevent acetate accumulation it is essential to control the temperature of the digester at 35°C. If the digester is operated without temperature control, it will not work properly except during the summer months. As the average ambient temperature is only about 25°C in August, the hottest month in Korea, temperature control of anaerobic digesters is essential for efficient anaerobic digestion. As shown in Figs. 3, 4, and 5, the simulation results at various temperatures are in good agreement with the experimental data. To simulate the long-term operations of anaerobic digestion, we will use the results of batch operations using the proposed model.

Verification of the Model in a Repeated Input System

Fig. 6 shows the cumulative gas production of real and simulation experiments when food waste was fed into the digester once a day at a concentration of 2 g VS/L. The model slightly overestimated the methane production and underestimated the carbon dioxide production. This is mainly due to the characteristics of Korean food waste, which is composed of a mixture of various food ingredients, having various degradation rates especially during the hydrolysis and acidification steps [20]. The amount of carbon dioxide generated in the early stages of digestion depends on the readily degradable portion of the food waste. If the readily degradable portion is present at high levels, carbon dioxide generation is high during the early stages of digestion (Fig. 2). Fig. 7 shows the profiles of VFA concentration, food waste and organic monomer concentrations at a repeated daily input of 2 g VS/L. The devised mathematical model matched the experimental results of operational acetic, propionic and butyric acid concentrations fairly well. Also it is shown that the system could

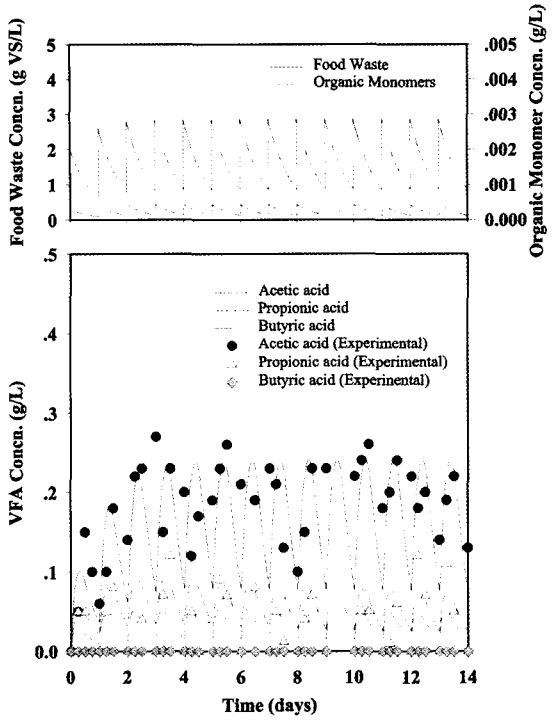

Fig. 7. Model prediction versus observed values of solid food waste consumption, organic monomer, and VFA concentrations in a repeated input operation at 2 g VS L^{-1} day^{-1} (Temperature = 35°C).

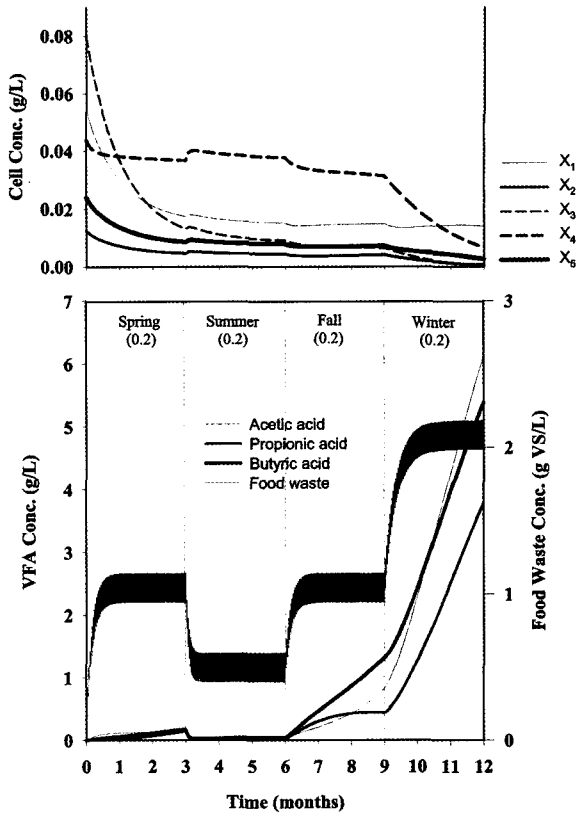

Fig. 8. Model prediction of solid food waste consumption, VFA, and bacterial group concentrations using a repeated input of 0.2 g VS L^{-1} day^{-1}, without temperature control.

handle 2 g VS/L day properly without evidence of food waste accumulations.

Effect of Temperature on Long Term Repeated Input Strategy

Korea has four distinct seasons, and thus the effect of seasonal temperature variations on the performance of the digester were investigated by simulation. It was assumed that the temperature during a season was constant and that the average temperature during spring, summer, fall, and winter were 15, 25, 15, and 5°C, respectively.

Fig. 8 shows the predictions for solid food waste, VFA, and bacterial group concentrations throughout the year when the digester was operated without temperature control. Food waste was charged repeatedly at a constant input rate of 0.2 g VS L^{-1} day^{-1}. The food waste concentration remaining in the digester was highest during the winter months and lowest during the summer months, i.e., it depended on the rate of hydrolysis and ambient temperature. The food waste concentration remaining in the digester is represented as an area due to the daily fluctuation of concentrations. VFA concentrations remained consistently low during spring and summer, and showed a continuous increase during the winter months. The digester could not be operated stably at the end of the winter due to the accumulation of VFAs. Bacterial concentrations decreased continuously from the start up because of the low input rate. As shown in Fig. 8, a constant repeated input for all seasons at 0.2 g VS/L day is improper, because it is too high during the winter and too low during the spring and summer, and justifies a change in the food waste input rate. Fig. 9 shows predictions of, solid food waste, VFA, and bacterial group concentrations from spring to winter at various input rates, namely, 0.5, 2.0, 1.5, and 0.2 g VS/L. In this case, the input rate of the solid food waste was adjusted according to the activities of bacterial groups. Even though the input rate in summer was ten times higher than that of the previous input rate of 0.2 g VS L^{-1} day^{-1} (Fig. 8), VFA concentrations, an indicator of digester stability, were extremely low. This is mainly due to the increased level of the various bacterial groups during the summer period. VFA concentrations in winter were lower than those in Fig. 8 and VFA concentration increase was minimal. From these results, it is evident that the amount of food waste charged into the digester should be controlled by taking seasonal temperature variations into consideration with respect to operational stability.

Effect of Food Loadings at 35°C

The digester cannot be operated efficiently unless the

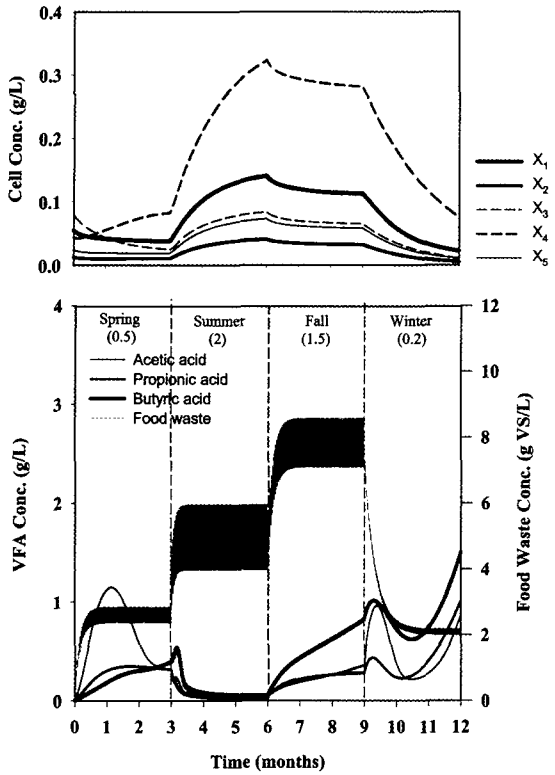

Fig. 9. Model prediction of solid food waste consumption, VFA, and bacterial group concentrations at various input rates, without temperature control. The input used rates were, 0.5, 2.0, 1.5, and 0.2 g VS L^{-1} day^{-1} for spring, summer, fall, and winter, respectively (The numbers inside parenthesis denote input rates in g VS L^{-1} day^{-1}).

temperature is controlled at 35°C, because the digester experiences severe variations in temperature far above the optimum temperature range. Thus, the simulation studies were carried out when the temperature of the digester was controlled at 35°C in a long term repeated input process.

Fig. 10 shows the predictions of, solid food waste, VFA, and bacterial group concentrations in the digester when the food waste was charged repeatedly every day for a year at a constant input rate of 3 g VS L^{-1} day^{-1}. The temperature of the digester was controlled at 35°C for throughout the year, and as a result, the VFA concentrations remained stable and at a low level after a month from the start up. This means that it is possible to charge additional amounts of food waste into the digester and to increase bacterial concentrations. Fig. 11 shows predictions of, solid food waste, VFA, and bacterial group concentrations for various input rates at 35°C. The input rate was started at 3 g VS L^{-1} $day^{-1}$and increased to 5, 8, and 10 g VS L^{-1} day^{-1}in a three month interval. Bacterial group concentrations increased gradually with time, and it is clear that VFA concentrations decreased with increased bacterial group concentrations. And, VFA concentrations increased dramatically when the input rate was increased, but concentrations decrea-

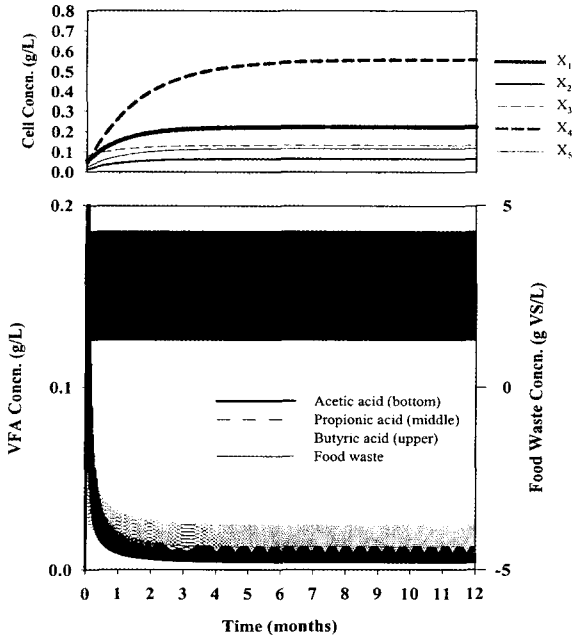

Fig. 10. Model prediction of solid food waste consumption, VFA, and bacterial group concentrations using a repeated input of 3 g VS L^{-1} day^{-1} with temperature controlled at 35°C. The dark areas of the bottom figure represents fluctuations in foodwaste concentrations.

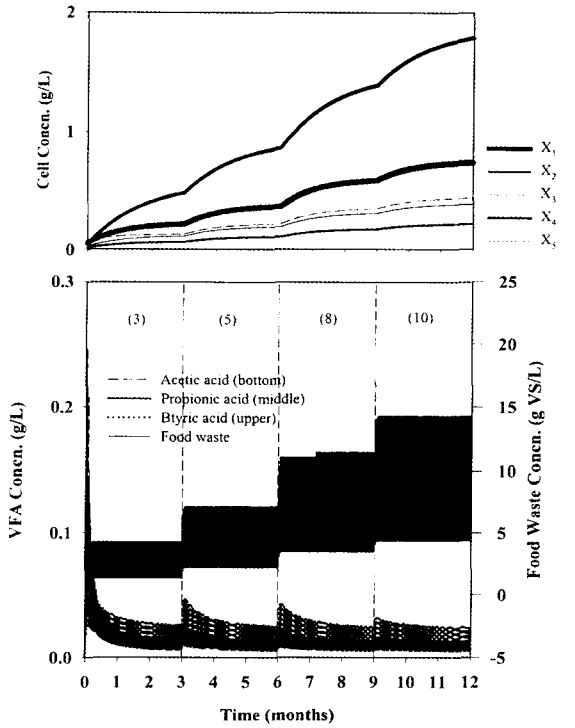

Fig. 11. Model prediction of solid food waste consumption, VFA, and bacterial group concentrations at various input rates with temperature control at 35°C. The input rate was strated at 3 g VS L^{-1} day^{-1} and increased to 5, 8, and 10 g VS L^{-1} day^{-1} at three month intervals (The numbers inside parenthesis denote input rates in g VS L^{-1} day^{-1}).

sed gradually as the bacterial group concentration increased. The bacterial group concentration can be increased in this way and the amount of food waste converted to biogas can be increased gradually. According to our simulation model even a 10 g/L loading can be used providing that the various acid concentrations remain low.

CONCLUSION

1) The current mathematical model for Korean food wastes decomposition was able to predict laboratory experimental results successfully regarding methane and carbon dioxide productions; volatile fatty acid concentrations at temperatures of 35, 25, and 15°C, respectively.

2) For a repeated daily feeding of 2 g VS/L at 35°C experimental and mathematical model results of cumulative CH_4 and CO_2 productions, and VFA concentrations.

3) Based on the above successful results repeated daily input of 0.2 g VS/L predicts VFA concentrations were very low in summer and spring, but increased gradually from fall to winter along with the accumulation of food wastes.

4) Seasonal manipulation of input loadings showed a possibility of handling more and successful food waste decompositions.

5) The model predicted that 3 g VS/L daily feeding will give a stable food waste decomposition at 35°C,

6) It is predicted that incremental feeding increase starting from 3 g VS/L can successful decomposition up to a daily 10 g VS/L. of food waste.

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