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Removal of organic matter and nutrients from food waste using a combined two-phase anaerobic digester and granular sequencing batch reactor system

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ABSTRACT

A unique system combining a two-phase anaerobic digester (AD) and a granular sequencing batch reactor (GSBR) was developed to remove organic matter and nutrients (nitrogen and phosphorus) from food waste. The start-up and stabilized performances of the AD were investigated by changing the organic loading rate (OLR). The AD effluent was treated using the GSBR process without using supplemental carbon sources or alkalinity. The combined system was capable of removing approximately 99% of the suspended solids, 99% of the chemical oxygen demand, 84% of the total nitrogen, and 88% of the total phosphorus. In addition, a modeling simulation was employed to estimate the net energy yield potential of the combined system. The simulation demonstrated that the two-phase AD and GSBR design can comprise an energy-producing system upon increasing the OLR to 1.5 kg/m^3/d. Therefore, the combined system can improve the removal of organics and nutrients, while also allowing for significant energy recovery. This study provides a novel approach for the design of a promising system that will improve the stabilization of organic waste.

Keywords: Anaerobic digestion; Aerobic granular sludge; Biogas; Food waste; Net energy yield

1. Introduction

Food waste is considered to be a main component of municipal organic waste; however, it is highly biodegradable and can be used for the production of biogas energy [1]. The disposal of food waste typically employs anaerobic digestion due to the high energy-recovering potential and limited environmental impact [2,3]. Nevertheless, the biotransformation of high-molecular organic compounds such as proteins and fats can result in high levels of organics and nutrients (nitrogen and phosphorous) remaining in the anaerobic digester (AD) effluent [4,5].

Methodologies that combine anaerobic digestion and activated sludge processes have been proposed by several researchers for the post-treatment of AD effluent [6,7]. These combined systems can simultaneously remove additional organic matter and remaining nutrients while also reducing the operating energy and supplementation requirement (additional carbon source) [8]. The effective removal of organic matter and nutrients, while also maximizing biogas production by anaerobic digestion, remains a main challenge in combining anaerobic digestion with activated sludge processes [9].

Aerobic granular sludge is considered to be a self-immobilized compact biomass formed under aerobic conditions. Aerobic granular sludge treatment processes yield efficient solid/liquid separation and use a unit design that requires a small footprint; these reduced space requirements lead to cost savings [10]. The mechanisms developed

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based on experiments and modeling have demonstrated the ability to simultaneously remove organic matter and nutrients in a one-step reactor by using aerobic granular sludge [11,12]. However, this technology has not been investigated in combination with anaerobic digestion processes as a post-treatment alternative.

There are several expected benefits that may be obtained by combining anaerobic digestion with aerobic granular sludge processes. For example, high-energy consumption can be compensated for by producing heat energy (methane gas) and reducing aeration space. Moreover, organic matter and nutrients can be simultaneously removed in a single reactor and the digester effluent is appropriate for the aerobic granular sludge process because it contains biodegradable organic matter and high-strength ammonium. Accordingly, in this study, a combined two-phase AD and granular sequencing batch reactor (GSBR, aerobic granulation reactor) system were developed for food waste disposal. The estimated performance for the combined system includes organic matter and nutrient removal, biogas production and composition, and variations in volatile fatty acids (VFAs). Furthermore, energy consumption and production models were employed to simulate the net energy yield potential of the system.

2. Materials and methods

2.1. Reactors

2.1.1. Two-phase mesophilic anaerobic digester

A two-phase mesophilic AD and GSBR were combined in this study (Fig. 1). The reactor was a cylindrical acrylic glass vessel. The AD consisted of an acidogenesis reactor (A-reactor) for pre-fermentation and a methanogenesis reactor (M-reactor) for biogas production. Both are continuous stirred-tank reactors without recycling; thus, the hydraulic retention time (HRT) is equal to the solid retention time. Mesophilic temperatures of 38°C in both the acidogenesis and methanogenesis reactors were maintained by heat exchangers throughout the experiment. Complete mixing conditions were achieved via mechanical stirring systems. The effective volumes of the A-reactor and M-reactor were 6 and 60 L, respectively. The AD effluent was delivered to the centrifuge reactor, where most of the suspended material was removed.

2.1.2. Granular sequencing batch reactor

After the centrifuge solid/liquid separation, the digester effluent was pumped to the GSBR for the aerobic granular sludge process. The reactor had a height of 150 cm, a diameter of 6 cm, and a working volume of 2.85 L. The air that provided supplemental oxygen was introduced through the bottom by a fine bubble air blower. One cycle of the reactor consisted of a 2 min influent filling, 358 min aeration time, 1,070 min anoxic time, 5 min settling time, and 5 min effluent discharge. During the anoxic time, the inside sludge and liquid were continuously mixed by a mechanical stirrer. The structure and operating strategy of the reactor allow for the formation of aerobic granules by generating a hydraulic shear force in the reactor [13,14]. The dissolved oxygen concentration detected in the reactor ranged between 2 and 3 mg/L, while the pH varied between 6.8 and 8.5.

2.2. Characteristics of food waste and sludge inoculation

The food waste for the feed and the digested sludge for the seed were obtained from a food waste treatment facility in Chungju, Korea. Table 1 shows the influent characteristics of the food waste. The GSBR process was seeded with activated sludge from a municipal wastewater treatment plant in Ansan, Korea. The acclimation period for the GSBR process, during which time the AD effluent was fed, was 1 month.

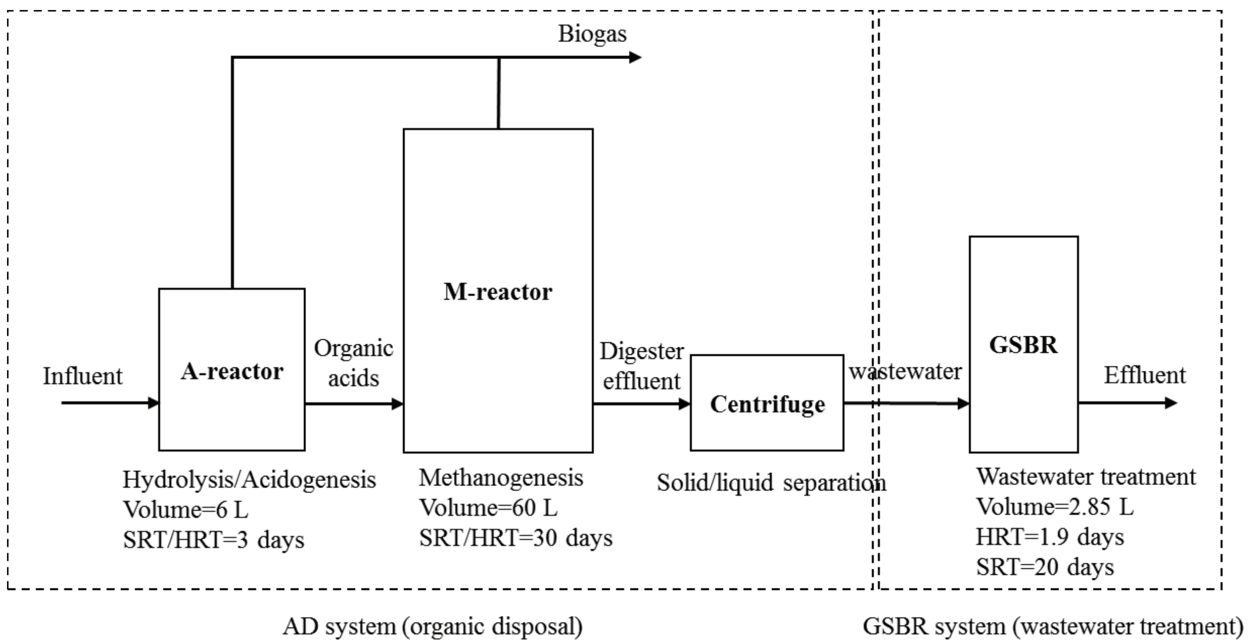

Fig. 1. Schematic diagram of the two-phase AD and GSBR system.

Table 1
Characteristics of influent food waste.

Item	Unit	Value (Average ± SD)
TCOD	mg/L	220389 ± 48253
SCOD	mg/L	115833 ± 40179
TN	mg/L	4683 ± 1893
TP	mg/L	2000 ± 950
NH_4^+	mg/L	199 ± 132
Cl^-	mg/L	2609 ± 1800
Na^+	mg/L	3371 ± 61
SO_4^{2-}	mg/L	222 ± 204
PO_4^{2-}	mg/L	790 ± 486
TS	mg/L	153000 ± 29319
VS	mg/L	142958 ± 28585
TSS	mg/L	99300 ± 24443
VSS	mg/L	96700 ± 24668
VS/TS	%	93
VSS/TSS	%	97
pH	–	4–5

SD: standard deviation; TCOD: total chemical oxygen demand; SCOD: soluble chemical oxygen demand; TN: total nitrogen; TP: total phosphorus; TS: total solids; VS: volatile solids; TSS: total suspended solids; VSS: volatile suspended solids.

2.3. Operating strategy

For the operation of the two-stage AD, the organic loading rate (OLR) was increased from 0.5 to 4 kg VS/m^3/d by diluting the influent with tap water. The operation of GSBR started when the organic removal and biogas production stabilized in the two-phase AD process (after 140 d). The GSBR did not use additional carbon sources or alkalinity for denitrification.

2.4. Simulation model for energy yield

The potential of the system energy yield was simulated by employing energy consumption and production models. In this study, only aeration and heating were considered to estimate the energy consumption; the pumping energy was neglected. The calculation of heating energy was carried out using the following equation [15]:

$$E_h = Q_{\mathrm{AD}} \cdot \rho_w \cdot c_p \cdot (T_2 - T_1) \tag{1}$$

Here, E_h is the heating energy (kWh/d), Q_{AD} is the influent flow rate of the two-phase AD (m^3/d), ρ_w is the density of water (1,000 kg/m^3), c_p is the specific heat capacity of water (0.001167 kWh/kg/°C), T_1 is the influent temperature, and T_2 is the operating temperature of the two-phase AD (38°C).

The oxygen demand (OD) of the GSBR process was calculated as follows:

$$\mathrm{OD} = \Delta\mathrm{COD} + 4.57 \cdot \Delta\mathrm{NH_3 - N} \tag{2}$$

Here, ΔCOD represents the chemical oxygen demand (COD) oxidized in the GSBR (kg/m^3), and ΔNH_3–N denotes the ammonia oxidized in the GSBR (kg/m^3).

The energy footprint per unit OD (EF, kWh/kg O_2) can be described using the adiabatic equation [16]:

$$\mathrm{EF} = \mathrm{w} \cdot \mathrm{R} \cdot \mathrm{T} \cdot [(p_2 / p_1)^n - 1] \cdot [c \cdot n \cdot e \cdot \left(\mathrm{COD_{In}} + 4.57 \cdot \mathrm{NH_3 - N_{In}}\right)]^{-1} \tag{3}$$

Here, w is the weight of air flow (kg/s), R is the engineering gas constant for air (8.314 kJ/mol/K), T is the ambient temperature (K), p_1 is the absolute inlet pressure (0.98 atm), p_2 is the absolute outlet pressure (1.48 atm), n is the ratio of the specific heat (0.283 for air), c is the molecular weight of air (29 kg/kmol), and e is the combined motor and blower efficiencies (70%).

Then, the energy consumption by aeration (E_{Air}, kWh/d) can be determined using the following equation:

$$E_{\mathrm{Air}} = Q_{\mathrm{GSBR}} \cdot \mathrm{OD} \cdot \mathrm{EF} \tag{4}$$

Here, Q_{GSBR} is the influent flow rate of the GSBR (m^3/d).

The production of heat energy from methane gas was considered as the only obtainable energy in the system. The heat energy production of methane gas (E_{CH4}, kWh/d) was calculated using the following equation:

$$E_{\mathrm{CH4}} = Q_{\mathrm{AD}} \cdot Y_{\mathrm{CH4}} \cdot \Delta\mathrm{COD}_{\mathrm{AD}} \cdot U_{\mathrm{CH4}} \tag{5}$$

Here, Y_{CH4} is the methane yield coefficient (estimated as 0.18 kg CH_4/kg COD), ΔCOD_{AD} is the amount of COD removed in the A-reactor (kg/m^3), and U_{CH4} is the energy density of methane (13.9 kWh/kg CH_4).

The net energy yield (E_{Yield}, kWh/d) was calculated by subtracting the aeration and heating energy consumptions from the heat energy production of methane:

$$E_{\mathrm{Yield}} = E_{\mathrm{CH4}} - (E_{\mathrm{AD}} + E_{\mathrm{Air}}) \tag{6}$$

2.5. Analytical methods

The samples analyzed in the experiment included influent food waste, A-reactor effluent, M-reactor effluent, biogas production, centrifuge effluent, and GSBR effluent. The total solids (TS), volatile solids (VS), total suspended solids (SS), mixed liquor volatile suspended solids (MLVSS), and sludge volume index (SVI) were determined according to standard methods (APHA, 2005). The COD, total nitrogen (TN), and total phosphorous (TP) were measured using a spectrophotometer (DR/2500, Method 8038, Hach Co., USA). The temperature and pH were measured using a pH meter (Horiba D-51, Horiba, Korea). The total biogas volume was measured automatically every day using a gas flow meter. The biogas composition was determined using a gas meter (GFM-406, Applied Conc. CH_4, CO_2: 100%; H_2S, H_2: <5,000, 1,000 ppm; Gas Data Ltd., UK). VFAs were determined by gas chromatography (Agilent 7890a FID, USA; carrier gas, N_2; injector temperature, 252°C; column temperature, 145°C; detector temperature, 250°C). MATLB software was used to write the program used for the calculations (MATLAB R2012a, MathWorks, USA).

3. Results and discussion

3.1. Performance of the two-phase anaerobic digestion process

The two-phase AD, which consists of acidification and methanogenic processes to convert the majority of organics to biogas, was the main component of the system. As a first step, the A-reactor was operated to hydrolyze solid organics into a soluble form and convert high-molecular organics to low-molecular VFAs, which favor the following methanogenic process. The A-reactor holds self-cultivated microorganisms from the food waste as opposed to using external microbial inoculation. In addition, it was operated with a short HRT of 3 d to prevent the loss of VFAs by the growth of methanogens. Fig. 2 shows the changes of SS (total suspended solids (TSS) and volatile suspended solids (VSS)) in the influent and effluent. Throughout SS monitoring, the VSS concentrations were close to the TSS concentrations, which indicates that the major compounds of solid wastes were organic matter. Stable and significant removal of SS (about 70%) was determined after 150 d. A greater increase in the soluble chemical oxygen demand (SCOD) concentration of the effluent compared with the influent was determined upon the removal of SS. Therefore, most of the solid organics in the food waste were hydrolyzed into simpler and soluble organic compounds.

The production of VFAs by acidogenic fermentation can occur after hydrolyzing the solid organics. The concentration of VFAs that can be converted into methane and carbon dioxide through a methanogenesis step is an important parameter for understanding and controlling the anaerobic biogas process. The changes in VFAs are shown in Fig. 3. Typical VFAs contain acetic, propionic, and butyric acids, which have frequently been reported in anaerobic digestion studies, and were monitored throughout the experiment [17,18]. Even though propionic and butyric acids were present, the dominant chemical in the VFAs was determined to be acetic acid. In the anaerobic digestion process, acetic acid can be directly used by methanogens, whereas propionic acid and butyric acid must first be oxidized into acetate [19]. Therefore, the higher concentration of acetic acid could result in a desirable biogas process that favors methane gas production.

The two-phase AD was operated by increasing the OLR in a stepwise manner. The monitored parameters used to estimate anaerobic digestion were organics (COD) removal, change in VS, biogas production, and change in pH (Fig. 4). A stable COD removal >80% was determined after increasing the OLR to 1.5 kg VS/m^3/d. However, at a higher OLR, the removal efficiency was not further improved. Accordingly, it was estimated that the start-up period took around 150 d. The profile of biogas production was related to OLR and organic

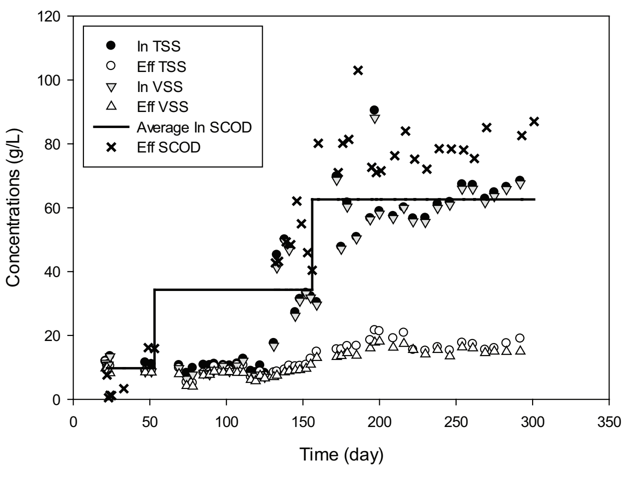

Fig. 2. Suspended solids removal and SCOD changes in the A-reactor.

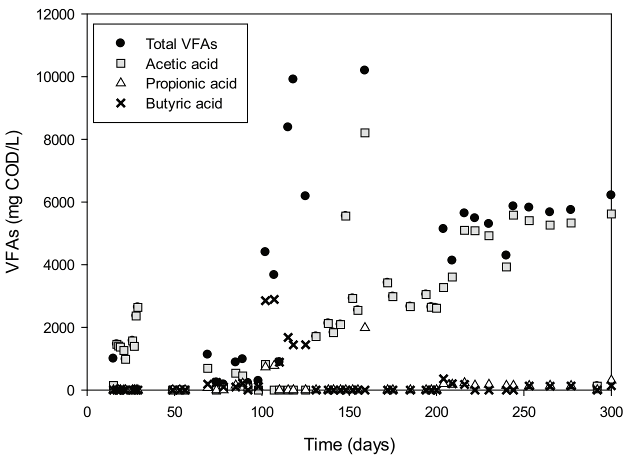

Fig. 3. Variations of VFAs in the acidification process.

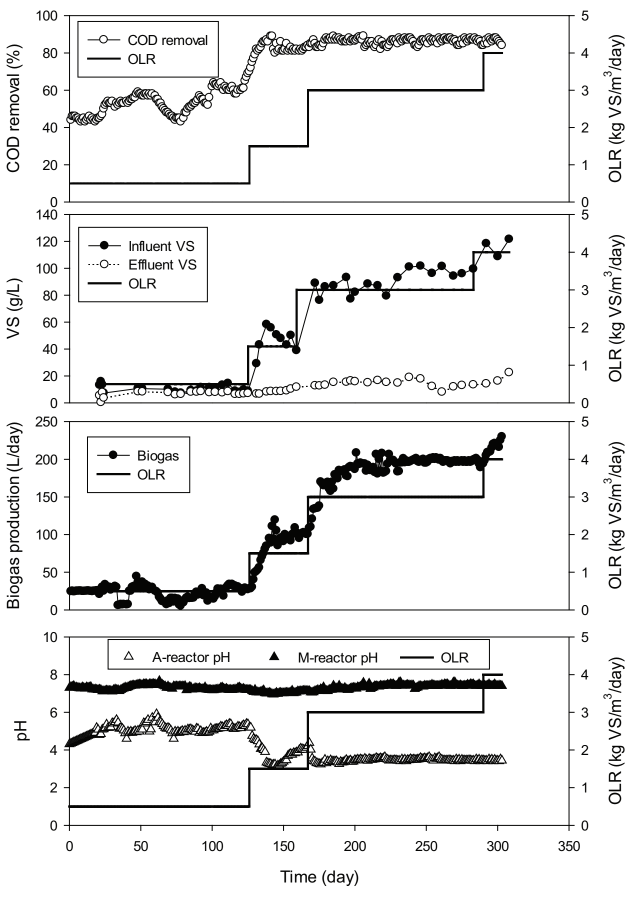

Fig. 4. Performance of the anaerobic digestion process with increasing OLR.

removal. The biogas production gradually increased and showed a stable rate after the start-up period. The A-reactor showed an acidic pH, which decreased dramatically to <4 after increasing the ORL to 1.5 kg VS/m^3/d. This might indicate an increased concentration of VFAs, which would result in a pH decrease. The pH in the M-reactor was stable between 7.0 and 7.5, which is suitable for biogas production. In conclusion, a successful start-up of the two-phase AD was achieved, and organic removal and biogas production were stable as the OLR was increased.

Carbon dioxide and methane are typically considered to be the main components of anaerobic biogas. In addition, the energy recovery of anaerobic digestion relies on methane gas, which can provide significant heat energy. Accordingly, the composition of biogas that was determined after the start-up period included carbon dioxide, methane, hydrogen, and hydrogen sulfide (Fig. 5). In the A-reactor, the acetic environment and low HRT can effectively inhibit the growth of methanogens. As a result, the main composition of the biogas was determined to be carbon dioxide and non-methane gases. In the M-reactor, the methane gas accounted for around 60% of the composition, while the carbon dioxide gas represented <40%. This demonstrated that the acidogenesis effect of the A-reactor and the methanogenesis effect of the M-reactor combined to achieve an ideal biogas process. The concentrations of hydrogen and hydrogen sulfide gases were low (on the order of parts per million, 0.0001%). Hydrogen gas was mainly produced in the A-reactor, and the amount of hydrogen sulfide gas was much higher than that of hydrogen gas in the M-reactor. In conclusion, this system demonstrated reliable biogas production for the recovery of significant heat energy by producing stable methane gas.

3.2. Performance of the GSBR process

The effluent of the AD contained high-strength organics (COD) and nutrients (TN and TP) that must be treated by a post-wastewater treatment process. In this study, the aerobic granular sludge process was employed to treat the AD effluent. The GSBR was operated after 140 d when stable organic removal was achieved by the two-phase AD process. Most of the solid organic and nutrient compounds were removed via centrifugal solid/liquid separation before operating the GSBR. Subsequently, the average concentrations of COD, TN, and TP in the influent wastewater were 2,010, 776, and 82 mg/L, respectively. The formation of self-aggregated dense biomass, which settles much faster than conventional activated sludge, is a particular characteristic of the aerobic granular sludge process [13]. The formation of granular sludge can be estimated by the sludge settleability parameter (SVI), which decreases according to the sludge composition. Therefore, the SVI and biomass concentration (MLVSS) changes and COD, TN, and TP removal amounts were monitored to estimate the performance of the GSBR process (Fig. 6). The SVI gradually decreased to <40 mL/g, indicating that a rapidly settling granular sludge was formed in the reactor. The aerobic granules (diameter 0.3–1 mm) could be detected after 60 d operation. Then, the removal of organic matter (COD) and nutrients (TN and TP) by the aerobic granular sludge was improved (compared with the activated sludge flocs). After the anaerobic digestion process, most of the biodegradable organic matter could be consumed by anaerobic microorganisms; thus, the wastewater contained a large amount of organic matter that was difficult to biodegrade. As a result, the capable COD removal was around 50%. Insufficient

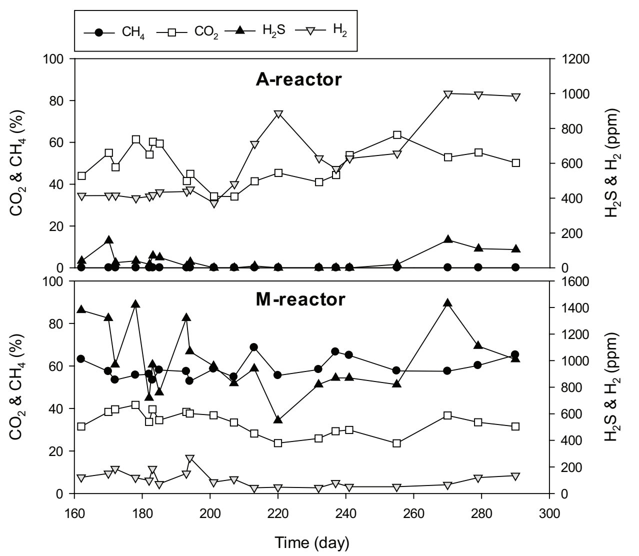

Fig. 5. Biogas composition produced by the two-phase anaerobic digester.

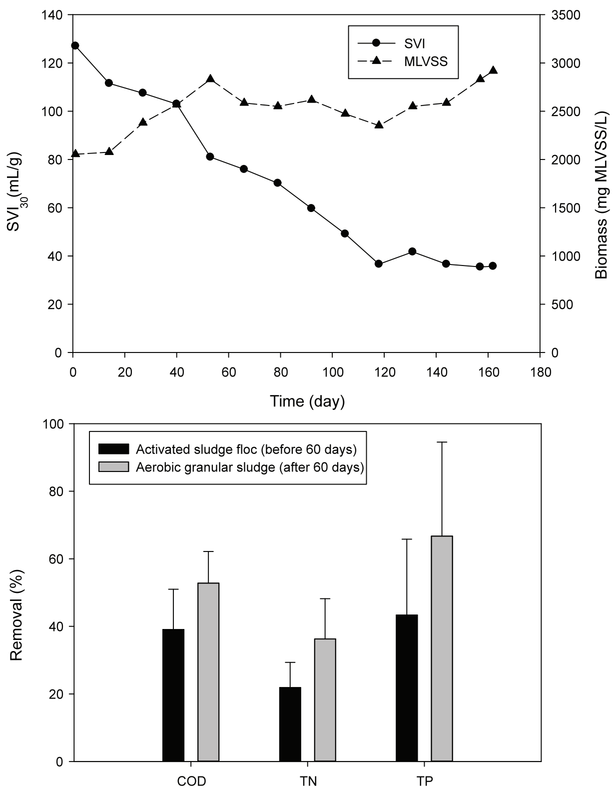

Fig. 6. Demonstration of aerobic granulation by changes in SVI and MLVSS, and the comparative removal performance between activated sludge flocs and aerobic granular sludge.

amounts of available organic carbon sources also affected the denitrification performance, which resulted in a low nitrogen removal (<40%). Aerobic granulation using the aerobic/anoxic cycle can provide conditions for the proliferation of polyphosphate-accumulating organisms when enough phosphate and a proper sludge retention time are available. However, cyclic phosphate release/uptake can result in complicated variations of the phosphate concentration in the effluent [20]. Therefore, although phosphorous removal was improved by the aerobic granular sludge, the removal rate varied widely between 30% and 80%. Nevertheless, the GSBR process demonstrated the ability to simultaneously remove organics and nutrients with a single-reactor operation.

3.3. Overall performance of the two-phase AD and GSBR system

The overall removal values (SS, COD, TN, and TP) of the two-phase AD and GSBR system were estimated for the operating period with an OLR of 3 kg/m^3/d; this demonstrated long-term stable removal (Fig. 7). The removal of both organic matter (COD) and solids (SS) was as high as 99%. The remaining organic matter and solids in the final effluent were either organics that were difficult to biodegrade or SS that did not settle. The effluent nitrogen concentration increased compared with the influent, which may be caused by ample nitrogen compounds in the microbial cells (sludge) from the mixed liquor [21]. In the same manner, the phosphorous concentration in the effluent of the two-phase AD was greater than that of the influent. Nevertheless, most of these nutrients (TN and TP) were removed by the post-centrifugation and GSBR processes. As a result, the overall TN and TP removal amounts were 84% and 88%, respectively.

3.4. Energy yield of the system

Under full-scale operation, the two-phase AD and GSBR system requires a significant amount of heating energy to maintain the mesophilic environment in the reactor. In general, most of the energy requirements in the activated sludge process are related to the electric power required to operate the aeration blower [22]. Therefore, the main energy consumers of the system are the heating installation and the aeration blower. However, the two-phase AD system can generate a considerable amount of heat energy from the production of methane gas. Furthermore, compared with conventional aerobic biological treatments, more energy conservation is expected in the GSBR process, because this process simultaneously removes organic matter and nutrients in a single-stage reactor. In this study, a simulation model was employed to estimate the system energy balance between main energy consumption and production (Fig. 8). A negative energy yield (energy loss) was determined at an OLR of 0.5 kg/m^3/d. However, the daily energy yield dramatically increased after increasing the OLR and stabilizing the system. It was demonstrated that this system has great potential to reduce and cover the energy losses, thereby creating an energy-yielding process.

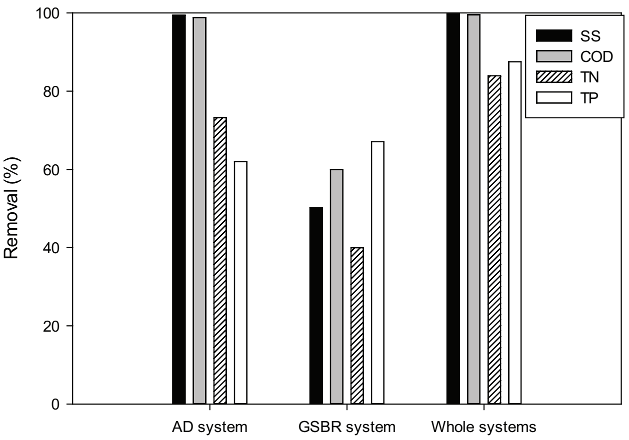

Fig. 7. Overall removal performance of the two-phase AD and GSBR system.

4. Conclusion

The two-phase AD process demonstrated stable, high organic removal, and biogas production after the start-up period. The biogas was mainly composed of methane gas, allowing considerable heat energy to be obtained. A compact, round-shaped granular sludge was formed in the GSBR using the AD effluent. Therefore, the aerobic granular sludge process can be used as an alternative technology in combination with anaerobic digestion. This technology saves energy and lowers costs due to its simultaneous removal of organics and nutrients in a single reactor. High overall removals of COD (99%), SS (99%), TN (84%), and TP (88%) were achieved in the combined system for food waste disposal. The model simulation demonstrated that the energy production from methane gas and the energy savings from the GSBR operation resulted in a positive net energy yield in the combined two-phase AD and GSBR system.

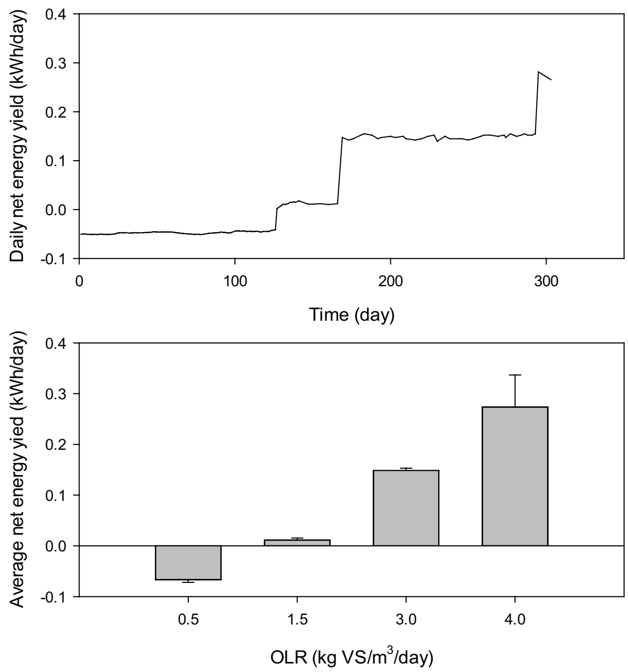

Fig. 8. Simulation results of net energy yield.

Acknowledgment

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References

[1] M. Fehr, M.D.R. Calcado, D.C. Romao, The basis of a policy for minimizing and recycling food waste, Environ. Sci. Policy, 5 (2002) 247–253.
[2] A. Tilche, F. Malaspina, Biogas Production in Europe, Paper Presented at the 10th European Conference Biomass for Energy and Industry, Wurzburg, Germany, 1998.
[3] M. Jabeen Zeshan, S. Yousaf, M.R. Haider, R.N. Malik, High-solids anaerobic co-digestion of food waste and rice husk at different organic loading rates, Int. Biodeterior. Biodegrad., 102 (2015) 149–153.
[4] G.N. Demirer, S. Chen, Two-phase anaerobic digestion of unscreened dairy manure, Process Biochem., 40 (2005) 3542–3549.
[5] J. Cheng, B. Liu, Swine wastewater treatment in anaerobic digesters with floating medium, Trans. ASME, 45 (2002) 799–805.
[6] L.W. Deng, P. Zheng, Z.I. Chen, Anaerobic digestion and post-treatment of swine waste water using IC-SBR process with bypass of raw wastewater, Process Biochem., 41 (2006) 965–969.
[7] D.H. Kim, E. Choi, Z. Yun, S.W. Kim, Nitrogen removal from piggery waste with anaerobic pre-treatment, Water Sci. Technol., 49 (2004) 165–171.
[8] F. Cui, S. Lee, M. Kim, Removal of organics and nutrients from food wastewater using combined thermophilic two-phase anaerobic digestion and shortcut biological nitrogen removal, Water Res., 45 (2011) 5279–5286.
[9] R. Rajagopal, P. Rousseau, N. Bernet, F. Béline, Combined anaerobic and activated sludge anoxic/oxic treatment for piggery wastewater, Bioresour. Technol., 102 (2011) 2185–2192.
[10] S.S. Adav, D.J. Lee, K.Y. Show, J.H. Tay, Aerobic granular sludge: recent advances, Biotechnol. Adv., 26 (2008) 411–423.
[11] F. Cui, S. Park, M. Kim, Characteristics of aerobic granulation at mesophilic temperatures in wastewater treatment, Bioresour. Technol., 151 (2014) 78–84.
[12] F. Cui, B. Kim, K. Mo, M. Kim, Characteristics of aerobic granulation at different organic and ammonium compositions, Desal. Wat. Treat., 54 (2015) 1109–1117.
[13] J.J. Beun, A. Hendriks, M.C.M. Van Loosdrecht, E. Morgenroth, P.A. Wilderer, J.J. Heijnen, Aerobic granulation in a sequencing batch reactor, Water Res., 33 (1999) 2283–2290.
[14] S.F. Yang, J.H. Tay, Y. Liu, Effect of substrate nitrogen/chemical oxygen demand ratio on the formation of aerobic granules, J. Environ. Eng., 131 (2005) 86–92.
[15] R. Khiewwijit, H. Temmink, H. Rijnaarts, K.J. Keesman, Energy and nutrient recovery for municipal wastewater treatment: how to design a feasible plant layout, Environ. Modell. Software, 68 (2015) 156–165.
[16] Metcalf and Eddy Inc., F.L. Burton, H.D. Stensel, G. Tchobanoglous, Wastewater Engineering: Treatment and Reuse, 4th ed., McGraw-Hill, New York, USA, 2003.
[17] Y.Y. Wang, Y.L. Zhang, J.B. Wang, L. Meng, Effects of volatile fatty acid concentrations on methane yield and methanogenic bacteria, Biomass Bioenergy, 33 (2009) 848–853.
[18] Y.G. Chen, S. Jiang, H.Y. Yuan, Q. Zhou, G.W. Gu, Hydrolysis and acidification of waste activated sludge at different pHs, Water Res., 41 (2007) 683–689.
[19] M. Kim, Y. Ahn, R.E. Speece, Comparative process stability and efficiency of anaerobic digestion; mesophilic vs. thermophilic, Water Res., 36 (2002) 4369–4385.
[20] J.B. Xavier, K.M. De Kreuk, C. Picioreanu, C.M.M. Van Loosdercht, Multi-scale individual-based model of microbial and bioconversion dynamics in aerobic granular sludge, Environ. Sci. Technol., 41 (2007) 6410–6417.
[21] T. Mankad, H.R. Bungay, Model for microbial growth with more than one limiting nutrient, J. Biotechnol., 7 (1998) 161–166.
[22] L.J. Pakenas, Energy Efficiency in Municipal Wastewater Treatment Plants: Technology Assessment, New York State Energy Research and Development Authority, 1995.