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Dry semi-continuous anaerobic digestion of food waste in the mesophilic and thermophilic modes: New aspects of sustainable management and energy recovery in South Korea

Dinh Duc Nguyen [a,b], Soon Woong Chang [b,*], Jae Hun Cha [a], Seong Yeob Jeong [a], Yong Soo Yoon [c], Sin Jin Lee [b], Minh Chi Tran [d], Huu Hao Ngo [e,*]

[a] Department for Management of Science and Technology Development & Faculty of Environment and Labour Safety, Ton Duc Thang University, Ho Chi Minh City, Viet Nam
[b] Department of Environmental Energy & Engineering, Kyonggi University, 442-760, Republic of Korea
[c] Department of Chemical Engineering, Dankook University, 448-701, Republic of Korea
[d] Institute for Tropicalization and Environment (ITE), Ho Chi Minh City, Viet Nam
[e] Centre for Technology in Water and Wastewater, School of Civil and Environmental Engineering, University of Technology, Sydney (UTS), Australia

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ABSTRACT

In this study, parallel, bench-scale, mesophilic and thermophilic, dry, semi-continuous anaerobic digestion (DScAD) of Korea food waste (FW, containing 22% total solids (TS) and 20% volatile solids (VS)) was investigated thoroughly under varying operational conditions, including hydraulic retention times (HRTs) and organic loading rates (OLRs). The aim was to evaluate the start-up, stability, overall removal efficiency, and inhibitory effects of toxic compounds on process performance over a long-term operation lasting 100 days. The results from both digesters indicate that the simultaneous reduction of VS and the production of gas improved as the HRT decreased or the OLR increased. The highest average rates of VS reduction (79.67%) and biogas production (162.14 m^3 biogas/ton of FW, 61.89% CH_4), at an OLR of 8.62 ± 0.34 kg VS/m^3 day (25 days of HRT), were achieved under thermophilic DScAD. In addition, the average rates of reduction of VS and the production of biogas in thermophilic DScAD were higher by 6.88% and 16.4%, respectively, than were those in mesophilic DScAD. The inhibitory effects of ammonia, H_2S, and volatile fatty acids (VFAs) on methane production was not clear from either of the digesters, although, apparently, their concentrations did fluctuate. This fluctuation could be attributed to the self-adaptation of the microbial well. However, digestion that was more stable and faster was observed under thermophilic conditions compared with that under mesophilic conditions. Based on our results, the optimum operational parameters to improve FW treatment and achieve higher energy yields could be determined, expanding the application of DScAD in treating organic wastes.

1. Introduction

Harnessing energy from waste benefits society and the environment and simultaneously conserves energy and creates a sustainable energy source. The greenhouse effect has led to adverse climate changes across the Earth and has become a cause of grave concern globally [1]. In order to reduce global greenhouse gas emissions significantly, multiple solutions need to be implemented concurrently, particularly in the major industrialized countries. Priority has to be given to ensuring that significant transition occurs from using fossil fuels to alternative energy sources that are cheap, renewable, and nonpolluting [2]. Renewable energy sources, such as tidal, geothermal, hydroelectric, and wind power could be employed in some countries. However, such sources are not expected to become the principal sources of energy in the near future [3].

Large quantities of food waste (FW) are produced worldwide every day. In South Korea, particularly, the average generation of FW reached 49,753 ton/day, accounting for 26.75% of the municipal solid waste over a period of 11 years, from 2003 to 2014 [4]. Generally, FW is the main waste stream of organic solid waste in urban areas [5]. Food waste could be considered a resource, as it represents a significant source of alternative energy [6,7].

Over the last several decades, ocean dumping, landfills, incineration, recycling as animal feed, and composting have been commonly employed for FW treatment. However, since the banning

* Corresponding authors.
E-mail addresses: nguyendinhduc@tdt.edu.vn (D.D. Nguyen), swchang@kyonggi.ac.kr (S.W. Chang), huuhao.ngo@uts.edu.au (H.H. Ngo).

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of ocean dumping, the space available for landfills has come under pressure and the associated government regulations have become stricter [8]. In addition, the land waste application is being managed increasingly to protect human health and the environment from the potentially harmful constituents typically found in FW, such as pathogens, heavy metals, and toxic organic chemicals [9–11]. Moreover, the incineration of FW could generate dioxins [10] and is energy intensive [12,13], whereas the recycling of FW as animal feed and compost is less in demand owing to the poor quality of the products [14]. However, dry anaerobic digestion (AD) is a feasible biological process, in which organic matter is degraded by the combined action of a highly diverse microbial community (consisting of several groups of microorganisms), and, subsequently, converted into biogas [15]. This technique has been developed and applied widely because of its economic advantages in comparison with the other treatment processes [16]. In recent years, dry AD from FW has increasingly caught the attention of scientists, mainly because of the advantages of the technique in comparison with wet AD. These include energy recovery, the capacity to operate at high OLRs [17], high rates of biogas production [18], applicability to a wide range of organic wastes, potential by-products [19], and cost-effective technology [18,20]. However, wet AD also has several advantages, such as smaller digester volumes, smaller footprint, lower leachate production, cheaper construction, and lower energy consumption [21].

In contrast with the advantages of the technique, dry AD has several limitations that have to be clarified, such as limited rates of methane production, longer retention and start-up time, large quantities of sludge seeding, the effects of accumulated VFA and toxic compounds, as well as sensitivity to small changes in the operating parameters (temperature, pH, nutrient, and others) [16,17,22,23]. However, extremely large quantities of FW with high organic matter are being produced in Korea daily. This presents an opportunity to utilize FW as a renewable energy source in the most effective way at an early stage. Concurrently, employing this technique responds to the waste-to-energy policy and the goal of the South Korean government to increase the portion of new and renewable energy by 2050 [24]. However, as the application of dry AD of FW in Korea is still in its infancy, there is a lack of research data on developing and applying this technique to match local conditions for potential energy recovery and sustainable FW management [25]. For these reasons, the modifications required for the sustainable operation of a dry AD process were employed in the FW treatment method followed in this study.

In this study, the mesophilic and thermophilic dry semi-continuous anaerobic digestion (DScAD) methods were evaluated and compared, with respect to their practical applicability for treating food waste (FW) at various high OLRs. In addition, this study comprehensively compared the performance of these two digesters in relation to the reduction of solids, production of biogas, percentage of methane in the biogas, and the effects of total volatile fatty acid (TVFA) and individual VFA on the methanogenic communities.

2. Materials and methods

2.1. Food waste and inoculation

Source-separated FWs were collected from restaurants located at Kyonggi University, crushed into small pieces to a diameter of less than 2 mm, and used as feedstock for the anaerobic digestion experiments. After crushing, small quantities of the FW, barely enough for daily feeding into the digesters, were placed in zipper bags and stored in a refrigerator at 4 °C. The inoculum sludge was collected from the FW digestion plant in Pusan city, South Korea. The characteristics of FW and inoculum sludge are shown in Table 1.

2.2. Digester setup, description, and operational conditions

A schematic diagram of the semi-continuous anaerobic digester system used in this study is shown in Fig. 1.

Two continuously stirred type digesters (digester A and digester B) were employed for mesophilic and thermophilic dry anaerobic digestion. The operating temperatures were 38 ± 0.1 °C for the mesophilic process and 55 ± 0.1 °C for the thermophilic process. Both digesters were equipped with a hot-water jacket system, which was thermostatically controlled by the re-circulating pump of the water heater. Each digester had an independent electric control system and agitator for constant churning at 30 rpm to ensure that the substrate and the inoculum were blended completely. All apparatus used in the systems were controlled automatically. The total volume of each digester was 20 L whereas the working volume was 10 L. Ten liters of seed sludge was added to the reactor and purged with N_2 gas for 10 min to create anaerobic conditions. The digesters were fed raw FW and withdrawal digestate every day at the same amounts of 100 g/day, 166 g/day, 333 g/day, and 400 g/L, during phase 1, phase 2, phase 3, and phase 4, respectively, corresponding to OLRs of 2.16 kg VS/m^3 day (phase 1), 3.58 kg VS/m^3 day (phase 2), 7.18 kg VS/m^3 day (phase 3), and 8.62 kg VS/m^3 day (phase 4). The corresponding hydraulic retention times (HRTs) were approximately 100 days, 60 days, 30 days, and 25 days, respectively, at a fixed solid content of 20% TS. After seeding the sludge, no FW was injected into nor sludge waste discharged from either digester for eight days. Additionally, both the digesters were operated at the same HRT, OLR, TS, and temperature conditions during phases 1 and 2. During phase 3, the temperature of the digester B was gradually increased from 38 °C to 55 °C at a rate of 1 °C every two days.

2.3. Analytical methods

The samples of influent and effluent digestion sludge and the biogas were collected and analyzed every day during the study period to evaluate the digester performance.

The concentration of total solids (TS), volatile solids (VS), total nitrogen (TN), ammonia nitrogen (NH_4-N), total phosphorus (TP), total chemical oxygen demand (TCOD), alkalinity (Alk.), and pH were measured according to standard methods [26]. The volume of biogas produced in the reactor was measured by using a wet gas meter (W-NK-0.5, Shinagawa Corporation, Japan) and a Tedlar bag for gas sampling. The analysis of the gas composition (CH_4, CO_2, NH_3-gas, and H_2S) was carried out by using a biogas analyzer (GSR-3100, Sensoronic Co., Ltd., South Korea). The amount of volatile fatty acids (VFAs) was determined by using a packed-column gas chromatograph (GC; Agilent 7890A, Agilent Technologies, Inc., USA), equipped with a flame ionization detector and SGE BP21 capillary wax column (25 m length × 0.53 mm ID × 0.5 μm df) (Agilent Technologies, Inc., USA), and with nitrogen as carrier gas. Approximately 2 μL of each sample was injected into the GC. The initial temperature of the GC column was 60 °C, which was increased at a rate of 5 °C/min to 120 °C. It was subsequently

Table 1
Characteristics of the food waste and inoculum sludge used in the experiment.

Parameters	Unit	Food waste	Inoculum
pH	–	4.91	7.62
Total solids (TS)	%	23.02 ± 2.22	20.02 ± 0.95
Volatile solids (VS)	%	20.55 ± 0.84	12.59 ± 0.71
VS/TS	%	91.53 ± 2.34	69.54 ± 2.30
Total chemical oxygen demand (TCOD)	g/kg	220	72
Total nitrogen (TN)	mg/kg	3650	4200
Ammonia nitrogen (NH_4-N)	mg/kg	900	1800