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

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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 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 oC. 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 oC for the mesophilic process and 55 ± 0.1 oC 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 oC to 55 oC at a rate of 1 oC 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 lm df) (Agilent Technologies, Inc., USA), and with nitrogen as carrier gas. Approximately 2 lL of each sample was injected into the GC. The initial temperature of the GC column was 60 oC, which was increased at a rate of 5 oC/min to 120 oC. 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

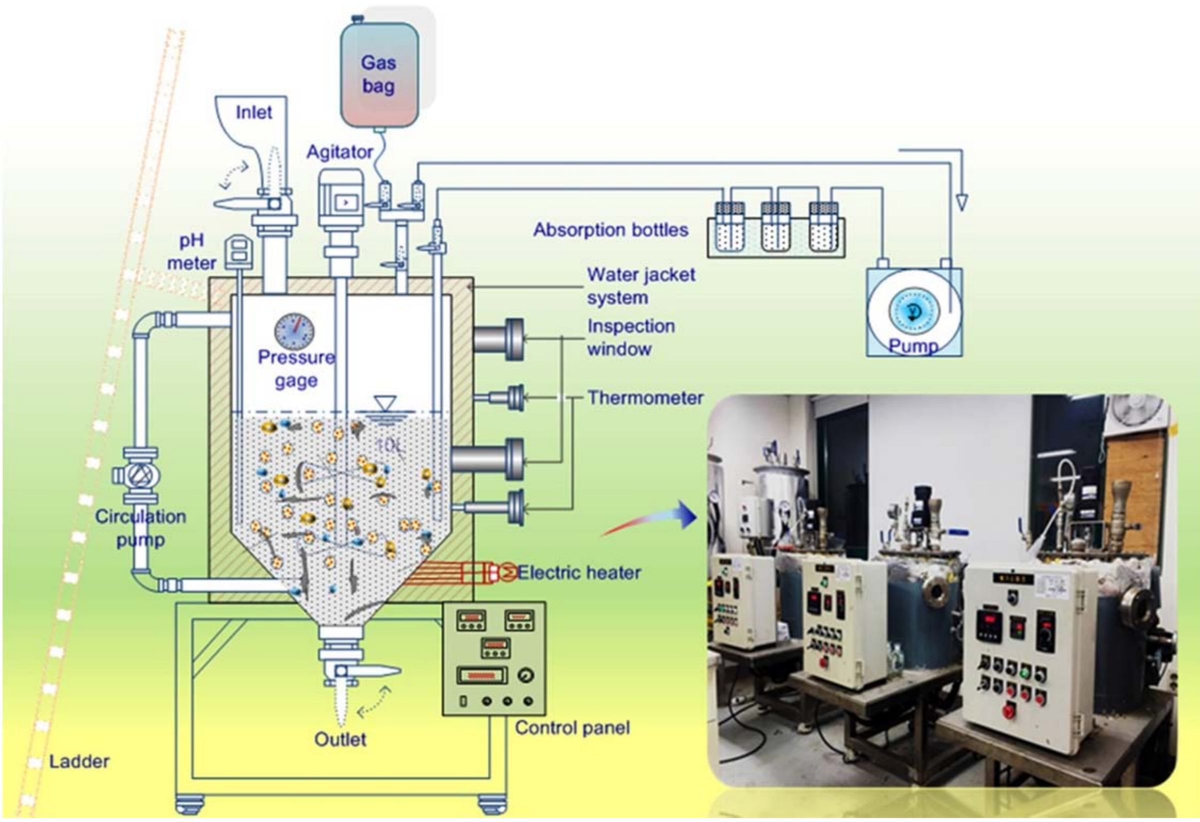

Fig. 1. Schematic diagram of the dry anaerobic digestion system.

increased at a rate of 10 oC/min to a final temperature of 230 oC. The injector temperature was set at 200 oC, while that of the flame ionization detector was set at 230 oC [27].

3. Results and discussion

3.1. Organic matter reduction

The consumption patterns of OLR and VS during the four operating periods of the dry semi-continuous anaerobic digesters were similar, as shown in Fig. 2. The ability of the system to adapt to the change in retention time was investigated, and the process in both digesters was stabilized. The results obtained (Fig. 2 and Table 2) indicate that during the course of the operation an increase in the biodegradation of the organic matter was observed when the consumption of organic matter increased (Fig. 2a). This occurred under both operating conditions, despite the increase in OLR (decrease in HRT), resulting in higher organic matter removal (Fig. 2b). Subsequently, this contributed to achieving greater efficiency and a favorable volumetric biogas production rate. Depending on the amount of organic load input, this would make it possible to predict the effect of reducing the amount of organic matter in anaerobic digesters.

The values of the operating organic loading rates (OLRo) applied to both DScAD were maintained at 2.16 ± 0.08, 3.58 ± 0.14, 7.18 ± 0.28, and 8.62 ± 0.34 kg VS/m^3 day, respectively, for phase 1 (HRT 100 days), phase 2 (HRT 60 days), phase 3 (HRT 30 days), and phase 4 (HRT 25 days).

As the results depicted in Fig. 2b demonstrate, the removal efficiency in each of the early phases in the digesters tended to be unstable owing to sudden changes in the operating OLRs. Therefore, to overcome this instability, an adaptation period was needed for the microorganisms in the digesters. Particularly in phase 1 and phase 2, a short period of one to two days was needed for the microorganisms to adapt; however, as the OLR increased, the time required for the microorganisms in the digester to adapt also increased, as can be seen in phases 3 and 4. For example, when the operating OLR reached 7.18 ± 0.28 kg VS/m^3 day (phase 3), the time needed for the anaerobic bacteria to adapt in both digesters was approximately five to eight days, which resulted in a VS reduction of 59–64%. Further, when the operating OLR increased by approximately 20% (8.62 ± 0.34 kg VS/m^3 day, phase 4), the minimum amount of time required to adapt was 26–30 days in order to achieve a VS reduction of 81.19 ± 2.68% under thermophilic conditions, and approximately 30–34 days to achieve a VS reduction of 72.99 ± 3.86% under mesophilic conditions.

In addition, the results showed that for the dry anaerobic digesters, the period of adaptation for anaerobic microbial activity after increase in the OLR was not only faster in thermophilic conditions but was also much more efficient in removing VS than under mesophilic conditions. These results show that higher consumption of specific organic matter and higher removal of VS were achieved within a relatively short acclimation period compared with those reported for municipal solid waste in other studies [28–32]. This suggests that the thermophilic DScAD carried out in this study was effective.

The evidence from the results mentioned above indicates that the highest VS removal efficiency was achieved during phase 4 (HRT 25 days, OLRo = 8.62 ± 0.34 kg VS/m^3 day) in both the ADs, whereas the thermophilic mode of operation was more stable, faster, and achieved higher VS reduction and higher OLR than the mesophilic mode. It is believed that thermophilic operating conditions create an environment that is more favorable to the growth and intense activity of the anaerobic microbial population.

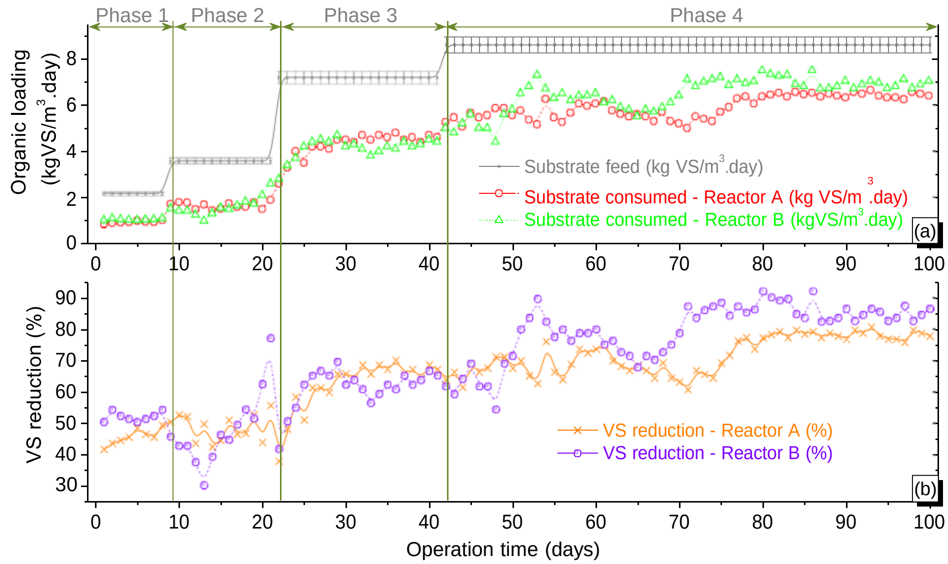

Fig. 2. Variation of OLRo, specific organic matter consumed (OLRc), and VS reduction in both anaerobic digesters during operation.

Table 2
Summary of the overall OLRs and VS reduction in each of the phases during operation.

Phase	HRT (days)	OLRo kg VS/m^3 day	Digester A VS removal (%)	Digester B VS removal (%)
1	100	2.16 ± 0.08	43.63 ± 2.4	48.84 ± 1.47
2	60	3.58 ± 0.14	46.39 ± 4.03	44.91 ± 11.3
3	30	7.18 ± 0.28	59.47 ± 7.72	57.52 ± 6.05
Steady state	30	7.18 ± 0.28	63.94 ± 1.81	58.62 ± 2.82
4	25	8.62 ± 0.34	68.63 ± 5.61	74.97 ± 8.52
Steady state	25	8.62 ± 0.34	74.54 ± 1.31	79.67 ± 1.72

Avg. ± Stdev.: Average ± Standard deviation.
Steady state: A period during a phase where the biological process is expected to have reached a state of stable performance.

3.2. Biogas production

The adaptation of the seeding inoculum to the feed stock and the operational conditions is an important issue in anaerobic digestion [30]. For dry anaerobic digestion, particularly, which involves the treatment of high concentrations of solids, the concentration of biomass in the reactor has to be high as well. However, the sludge from wet digesters, with a concentration of less than 5% VS, has often been used as a seeding source, which, however, requires a longer start-up period to develop a highly concentrated microbial community and achieve a stable performance [31,33,34]. In this study, dry digester FW with a VS concentration of 12.59 ± 0.71% was used as the main seeding source in an effort to reduce the start-up period. The success of this strategy is evident from the biogas and biomethane (CH_4) being generated in both digesters from the first day of the experiment (Figs. 3 and 4).

Four phases, corresponding to the four different values of solid retention times, were carried out to evaluate the effect of this parameter on the process performance of gas production at a fixed solid-content level of approximately 20% TS. The pH in AD is a crucial factor that can have a pronounced effect on microbial activities, thereby affecting the digester performance and biogas production. However, during each phase of this study, the variation in pH was found to be within a favorable range of 6.6–8.1. This was achieved despite the obvious increase in the OLR during each run period in both digesters, changes in the VFA levels, and the average concentration of alkalinity in the digester A being slightly higher than that in the digester B.

The variations in biogas generation and the specific gas yield in both digesters during the operation are shown in Figs. 3 and 4. As seen from the results presented in Figs. 3 and 4 and Table 3, the gas yield consistently increased in both digesters, despite the increase in OLRs or the decrease in HRTs. This means that the gas yield in the digesters increased as the OLRs increased, achieving an average rate of biogas production during treatment in phase 1, phase 2, phase 3, and phase 4, equal to 0.18 ± 0.07, 0.3 ± 0.09, 0.44 ± 0.06, and 0.53 ± 0.11 m^3 biogas/kg VS_{fed}, respectively, in digester A. An average rate of biogas production of 0.17 ± 0.06, 0.23 ± 0.16, 0.44 ± 0.07, and 0.58 ± 0.15 m^3 biogas/kg VS_{fed}, respectively, was achieved in digester B. In addition, the average biomethane content in the biogas produced was 41.31 ± 2.8%, 60.59 ± 5.29%, 56.9 ± 6.17%, and 60.79 ± 5.6%, respectively, in digester A, and 42.25 ± 2.6%, 55.15 ± 10.16%, 53.63 ± 3.81%, and 56.56 ± 5.32%, respectively, in digester B.

The results obtained for phase 4 indicate that the average specific gas production, the rate of biogas production, and the methane content in steady-state conditions (from the 87th day of investigation onwards) was 0.65 ± 0.03 m^3/kg VS_{fed}, 139.29 ± 6.08 m^3 biogas/ton FW, and 66.82 ± 1.93%, respectively, for mesophilic DScAD (Fig. 3). It was 0.75 ± 0.02 m^3/kg VS_{fed}, 162.14 ± 4.58 m^3 biogas/ton FW, and 61.89 ± 2.74%, respectively, for thermophilic DScAD (Fig. 4). Despite being generated simultaneously and under the same conditions, the yields of biogas (162.14 ± 4.58 m^3/ton FW) and methane (CH_4, 100.32 ± 4.59 m^3/ton FW) obtained from thermophilic DScAD were 16.4% and 7.87% higher than were those from mesophilic DScAD. However, the methane concentration was the

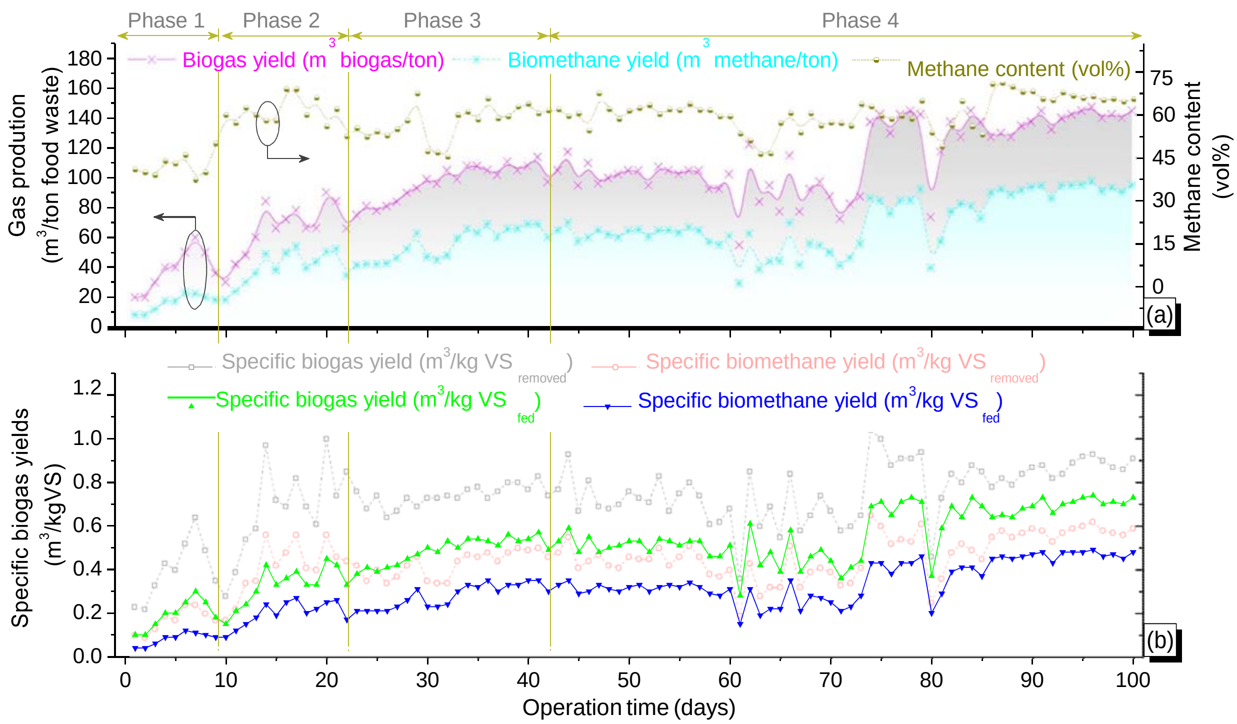

Fig. 3. Variation of biogas and biomethane production in digester A during the operation.

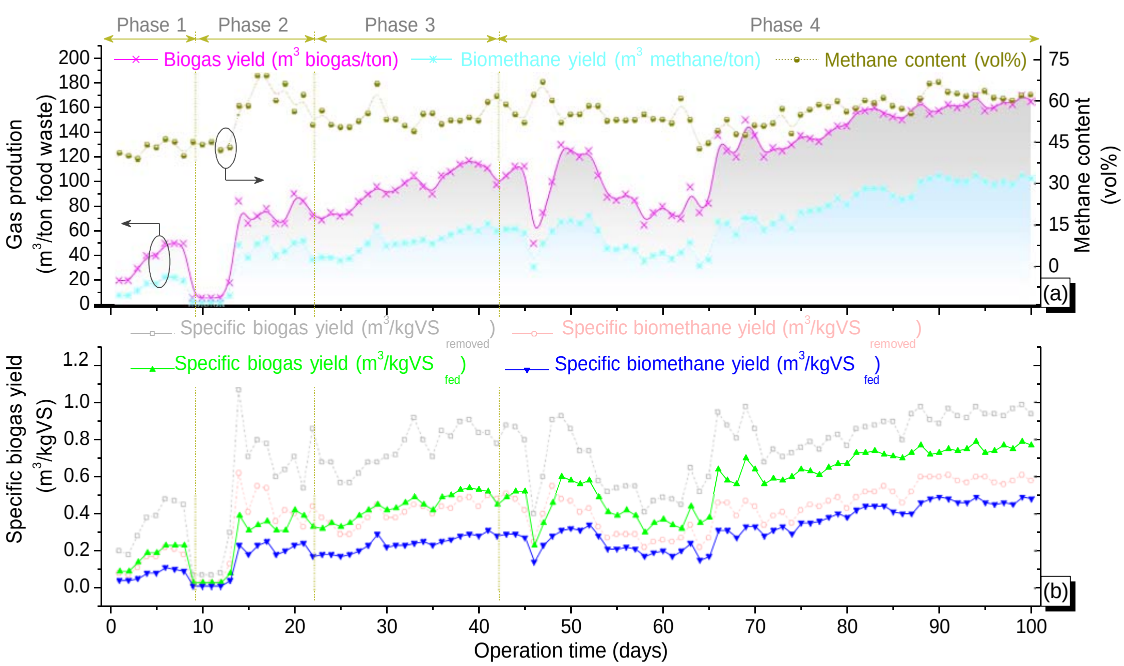

Fig. 4. Variation of biogas and biomethane production in digester B during the operation.

inverse of the biogas production, which could be explained by the rapid adaptation and presence of multiple active bacterial populations at high concentrations in the thermophilic DScAD. This accelerated the metabolism of organic compounds and, consequently, the biogas production, thereby expanding the potential for their application in treating organic waste. Other researchers [35,36] have also observed that the thermophilic digester achieved higher COD removal and biogas yield in comparison with the mesophilic digester during the anaerobic digestion of a combination of wastewater from an olive mill and waste from an abattoir.

Compared with various other studies [28,37,38], the technique used in this study not only required a shorter start-up time but also resulted in higher biogas production. Additionally, although the same anaerobic digester was used in each phase, the acclimation period required to achieve steady-state biogas production was 1.66–1.72 times longer than was the acclimation period required

Table 3
Summary of the performance of mesophilic and thermophilic DScADs at different OLRs.

Phase	OLRo	Biogas yield		CH_4 yield		
	(kg VS/m^3 d)	(m^3/kg VS_{fed})	(m^3/ton)	(m^3/kg VS_{fed})	(m^3/ton)	(% content)
Digester A						
1	2.16 ± 0.08	0.18 ± 0.07	38.75 ± 14.58	0.07 ± 0.03	16.03 ± 6.03	41.31 ± 2.81
2	3.58 ± 0.14	0.3 ± 0.09	63.49 ± 19.31	0.18 ± 0.06	38.78 ± 12.79	60.59 ± 5.29
3	7.18 ± 0.28	0.44 ± 0.06	95.5 ± 13.73	0.25 ± 0.05	54.64 ± 11.45	56.9 ± 6.17
Steady state		0.49 ± 0.02	105.65 ± 5.17	0.29 ± 0.04	61.89 ± 8.37	58.46 ± 6.48
4	8.62 ± 0.34	0.53 ± 0.11	114.31 ± 24	0.32 ± 0.08	70.11 ± 18.28	60.79 ± 5.6
Steady state		0.65 ± 0.03	139.29 ± 6.08	0.43 ± 0.01	93 ± 3.05	66.82 ± 1.93
Digester B						
1	2.16 ± 0.08	0.17 ± 0.06	37.5 ± 12.82	0.07 ± 0.03	16.03 ± 6.03	42.25 ± 2.6
2	3.58 ± 0.14	0.23 ± 0.16	50.05 ± 35.16	0.14 ± 0.1	30.46 ± 22.53	55.15 ± 10.16
3	7.18 ± 0.28	0.44 ± 0.07	93.84 ± 15.49	0.23 ± 0.04	50.41 ± 9.44	53.63 ± 3.81
Steady state		0.49 ± 0.04	104.83 ± 9.15	0.26 ± 0.03	55.87 ± 5.74	53.3 ± 2.76
4	8.62 ± 0.34	0.58 ± 0.15	125.94 ± 32.98	0.33 ± 0.1	71.92 ± 22.4	56.56 ± 5.32
Steady state		0.75 ± 0.02	162.14 ± 4.58	0.47 ± 0.02	100.32 ± 4.59	61.89 ± 2.74

Avg. ± Stdev.: Average ± Standard deviation.
The average and standard deviation were calculated based on the total samples of the phase, including the results of the samples during the unstable period.

to achieve stable metabolism of VS (Figs. 2–4). This could be explained by the time required after each increase of OLR to enable the population of organisms to become acclimated to the additional biodegradable organic resource, to grow, and to synthesize new cells.

These results reaffirm the higher yield of methane gas that has been achieved in the thermophilic digester (Table 3), indicating the success of the study to determine a potential source for biogas energy. In addition, these results can serve to predict the performance of the mesophilic and thermophilic digesters under different OLRs relevant to biogas production and the reduction of organic matter. Accordingly, this research has demonstrated that DScADs can serve the dual purpose of FW reduction and improvement of biogas production from treated FW at a high OLR. This finding demonstrates the potential for the reduction of the environmental footprint of the whole system and the high potential for energy recovery.

3.3. Accumulation of VFAs

Volatile fatty acids are the intermediary products of the anaerobic digestion process and are mainly produced by acidogenic and acetogenic bacterial populations [39,40]. The accumulation of VFAs in anaerobic digesters could have various causes, such as excessive organic loading, changes in temperature, lower ratio of inoculum, and the accumulation of toxic compounds [41–43]. The accumulation of large amounts of (TVFAs) in mesophilic and thermophilic anaerobic digesters can result in an imbalance in the fermentation process, which, ultimately, could lead to the failure of the process [44–47].

In this study, two parallel anaerobic digesters were operated under the same HRT, OLRo, and TS conditions in each phase. Other short-chain organic acids, for example valeric, caproic, and enanthic acids, are termed ‘‘etc. VFAs” in this study. Individual VFAs (acetic acid, propionic acid, butyric acid, and etc. VFAs) and TVFA in the mixtures in both anaerobic digesters are shown in Fig. 5. Overall, these increased proportionally with the increasing operating OLRo, with acetic acid and propionic acid being predominant, corresponding to a percentage concentration in the 53.9–77.1% and 15–42.3% range, respectively, in the digester A, and the 36.6–69.9% and 19.7–55.6% range, respectively, in the digester B.

The results obtained (Fig. 5, Table 4) indicate that the total concentration of VFAs in both the digesters during phases 1 and 2 was less than 0.25 g/L, but in phase 3 (OLRo of 7.18 ± 0.28 kg VS/m^3 day), the operating temperature of the digester B rose gradually from 38 oC to 55 oC, at a rate of 1 oC for two days, to ensure a thermophilic mode of operation, for which the DScAD had been designed. The concentration of TVFA increased during phases 3 and 4, to reach average values of 1.85 ± 0.65 mg/L (with 67.6 ± 9% acetic acid, 30.3 ± 8.6% propionic acid, and 1.6% butyric acid) and 4.49 ± 0.90 g/L (with 70.5 ± 7.1% acetic acid, 19 ± 4.2% propionic acid, and 3.3 ± 0.3% butyric acid), respectively, in the digester A. In digester B, the values were 1.77 ± 0.69 g/L (with 64.1 ± 4.6% acetic acid, 26.8 ± 6% propionic acid, and 6.7 ± 2.2% butyric acid) and 5.84 ± 1.02 g/L (with 50.5 ± 6.2% acetic acid, 30.7 ± 4.8% propionic acid, 11 ± 3.3% butyric acid), respectively. The NH_4-N concentrations in the samples gradually increased during the entire period of operation, from 1.38 g/L (phase 1) to 3.4 g/L (phase 4) in the dry anaerobic digester A, and from 1.8 g/L (phase 1) to 3.7 g/L (phase 4) in the dry anaerobic digester B. Consequently, a higher concentration of NH_4-N was found in the digester B compared with the digester A.

Interestingly, in both digesters, the peaks in TVFA concentration were observed on day 84, during phase 4. However, the TVFA levels were 25.2% higher in the digester B (thermophilic condition) than in the digester A (mesophilic condition). Once the maximum values of 5.67 g TVFA/L in the mesophilic mode (54.0% acetic acid, 29.1% propionic acid, and 4.1% butyric acid) and 7.10 g TVFA/L in the thermophilic mode (43.0% acetic acid, 32.5% propionic acid, and 10.6% butyric acid) had been reached, the TVFA returned to a stable level of 5.45 ± 0.03 g TVFA/L in the mesophilic mode (73 ± 2.8% acetic acid, 15.4 ± 0.3% propionic acid, and 3.9 ± 2% butyric acid) and 6.29 ± 0.50 g TVFA/L in the thermophilic mode (55.9 ± 3.9% acetic acid, 24.4 ± 0.2% propionic acid, and 15.1 ± 0.4% butyric acid). However, no decrease in pH was observed because of the accumulation of VFAs, while the alkalinity was maintained in the 10–11 g/L range as $CaCO_3$. Consequently, there was no reduction in the generation of methane because of the accumulation of VFAs.

Furthermore, the observed experimental results showed that the ratio of propionic acid/acetic acid varied in a range of 0.21–1.77 in the digester A and 0.28–1.52 in the digester B, whereas the concentrations of acetic acid negligibly increased during the course of the study. No significant differences emerged between the experiments in two digesters. However, the rate of increase was faster and higher in the concentration of acetic acid compared with the other VFAs, such as propionic acid and butyric acid.

It could be concluded from the results that the average accumulation of TVFAs was 15.44% higher in the thermophilic DScAD than in the mesophilic DScAD. The microorganism populations in both

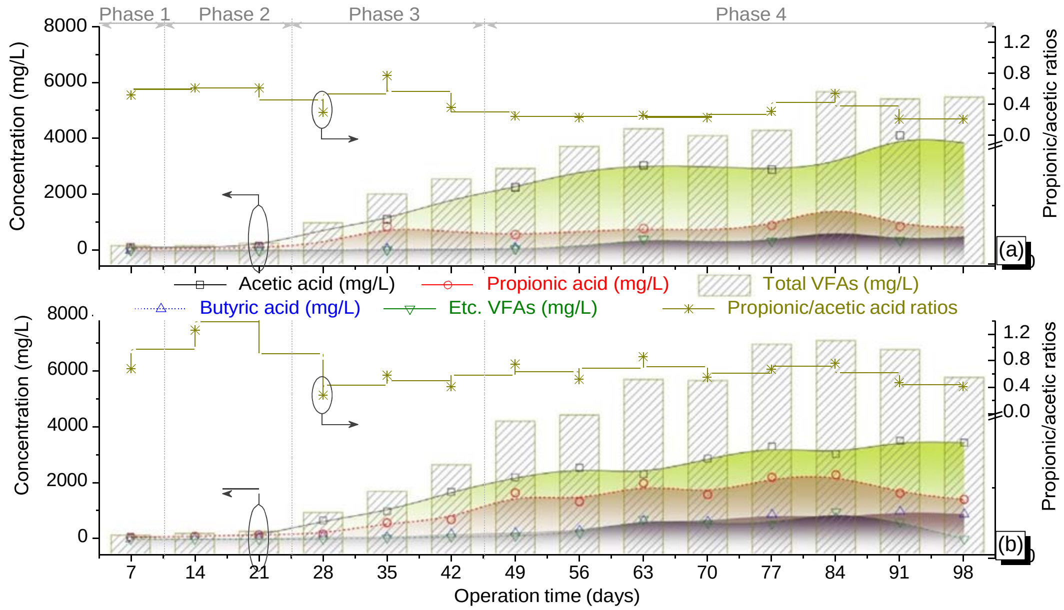

Fig. 5. Concentration of individual and total VFAs in the (a) anaerobic digester A and (b) anaerobic digester B during operation at different OLRs.

Table 4
Variation of volatile fatty acids in anaerobic digesters.

Phase	Acetic acid		Propionic acid		Butyric acid		Etc. VFAs	Total VFAs
	mg/L	%	mg/L	%	mg/L	%	mg/L	mg/L
In dry semi-continuous anaerobic digester A								
Phase 1	105	65.60	55	34	0	0	0	160
Phase 2	122 ± 23	59.7 ± 2.6	74.5 ± 14.5	36.4 ± 1.3	10 ± 10	3.9 ± 3.9	0	206.5 ± 47.5
Phase 3	1231.3 ± 456.4	67.6 ± 9	577.7 ± 262.2	30.3 ± 8.6	30.3 ± 10.8	1.6 ± 0	9.3 ± 8.2	1848.7 ± 649.1
Phase 4	3128.8 ± 548.2	70.5 ± 7.1	862.8 ± 314.9	19 ± 4.2	152.9 ± 83.9	3.3 ± 1.3	348.4 ± 195.5	4492.8 ± 901.8
Steady state	3975 ± 133	73 ± 2.8	836.5 ± 12.5	15.4 ± 0.3	212.5 ± 108.5	3.9 ± 2	423 ± 66	5447 ± 29
In dry semi-continuous anaerobic digester B								
Phase 1	88	59.50	60	40.50	0	0	0	148
Phase 2	95 ± 9	38.9 ± 2.3	133 ± 25	53.7 ± 2	18.5 ± 3.5	7.5 ± 0.3	0	246.5 ± 37.5
Phase 3	1122 ± 427.1	64.1 ± 4.6	491.7 ± 219.6	26.8 ± 6	112.3 ± 50.1	6.7 ± 2.2	48.7 ± 30.7	1774.7 ± 698.1
Phase 4	2917.5 ± 477.4	50.5 ± 6.2	1773.6 ± 336.2	30.7 ± 4.8	668.5 ± 260.3	11 ± 3.3	477.9 ± 308.4	5837.5 ± 1025.1
Steady state	3493.5 ± 35.5	55.9 ± 3.9	1536 ± 111	24.4 ± 0.2	946 ± 49	15.1 ± 0.4	312.5 ± 303.5	6288 ± 499

digesters were able to adapt to and withstand the changes in the VFA levels. The VFA exerted no apparent influence on the biogas production or performance of each dry anaerobic digestion process during the stable periods of the phases, despite the significant variation in the VFAs in the two digesters.

4. Conclusions

The proposed dry anaerobic digesters for FW with high solids content were thoroughly investigated to assess the performance and inhibitory effects of toxic compounds at different OLRs and HRTs. The main findings are:

- The stepwise increase in OLR resulted in a simultaneous increase in the reduction of VS and the production of biogas.
- The thermophilic mode of operation was faster, with higher treatment efficiency, compared with the mesophilic mode relevant to substrate degradation and biogas yield, even at higher loading rates.
- Increasing the OLR from 2.2 to 8.6 kg VS/m^3 day did not have any clear effect on either the operation of the microbial communities or the performance of the dry anaerobic digester during the stable periods of operation.
- VFA showed no apparent inhibitory effect on the rate of its conversion into biogas in either of the digesters.
- Acetic and propionic acids dominated the TVFAs during all phases of the both dry anaerobic digesters.
- The startup time interval required for the dry mesophilic and thermophilic anaerobic digestion systems to adapt depended on the OLR. However, digestion under the thermophilic conditions was observed to be more stable, faster, and efficient than under the mesophilic conditions.

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