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Two-stage anaerobic digestion of food waste and horticultural waste in high-solid system

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HIGHLIGHTS

- HSAD of food waste and horticultural waste was studied in two-stage process.
- HSAD of food waste failed within 3 days.
- Two-stage process showed better performance than one-stage codigestion.
- When the OLR was 4.00 gVS/(L·day), the two-stage process was stable.

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ABSTRACT

A two-stage process was proposed to increase biogas yield, efficiency and stability of the codigestion process of food waste, chicken manure and horticultural waste in a high-solid system. In this two-stage process, high-solid codigestion of food waste and chicken manure was carried out in the first stage and then, transferred and codigested with grass in the second stage. It was found that high-solid digestion of food waste failed after 3 days because of the accumulation of volatile fatty acids (VFAs). The two-stage process could be optimized by adjusting the mass ratio (based on volatile solids (VS)) among food waste, chicken manure, and grass, and a ratio of 4:5:5 of food waste to chicken manure to grass could lead to the highest biogas yield and efficiency. The biogas yield of the two-stage process 83.25% higher and the duration of digestion was 18 days shorter than those of the codigestion. The VS removal efficiency of the two-stage process was 57.30% higher than that of one-stage codigestion. When the organic loading rate (OLR) was 4.00 gVS/(L·day), the two-stage process was stable, with an average methane yield of 113.4 mL/gVS.

1. Introduction

Anaerobic digestion (AD) is a widely-used method to dispose of organic wastes because of its good performance in waste reduction and energy recovery in the form of methane [1]. AD can be divided into high-solid digestion (total solids (TS) > 15%) and wet digestion (TS < 15%), respectively. High-solid anaerobic digestion (HSAD) allows for a high organic loading rate and small reactor volume as well as low energy cost. The subsequent treatment of digestion residue is simplified compared to wet digestion [2]. However, HSAD process is much easier to be inhibited by inhibitory compounds such as organic acids or ammonia due to low moisture content, which can reduce digestion efficiency and cause instability.

High-solid anaerobic digestion of horticultural waste is limited by low hydrolysis rate, low digestion efficiency, and inhibition of volatile fatty acids (VFAs) [3]. Hydrolysis is the rate-limiting step for lignocellulosic substrate [4–6] whereas methanogenesis is the rate limiting step for easy biodegradable substrates such as food waste, which leads to the accumulation of VFAs [7,8]. Although food waste is a promising organic substrate for AD due to its high biochemical methane potential (BMP) and high organic matter content, HSAD of food waste often fails because of the rapid production of VFAs in the initial stage [9–11]. The optimal pH value of hydrolysis and methanogenesis is about 5.0–7.0 and 7.0–8.0, respectively [12]. Thus, it is possible to remove the inhibition of VFAs or ammonia or improve hydrolysis of lignocellulosic biomass using two-stage process by separation hydrolysis/acidogensis and methanogenesis [13,14]. While, in the reported two-stage process,

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the methanogenic stage is often carried out in a wet system with an up-flow anaerobic sludge bed/blanket (UASB) or a continuous stirred tank reactor (CSTR) which will increase the equipment and operation cost [15–16]. Yet, to the best of our knowledge, no studies have been carried out to remove the inhibition of VFAs and improve the hydrolysis of horticultural waste using two-stage process in high solid system.

A two-stage process was proposed to increase biogas yield and to stabilize the digestion process of horticultural waste and food waste in high-solid system. To date, few studies investigated the HSAD performance of food waste and were mainly focused on codigestion [17,18]. Codigestion of food waste and animal manure is a promising method to keep the digestion process stable and to increase biogas yield [19]. In this two-stage process, food waste and chicken manure are codigested in the first stage. When the digested food waste mixed with horticultural waste in the second stage, VFAs caused by acidogensis of food waste are diluted and the slightly low pH is beneficial for the hydrolysis of horticultural waste [12]. The two-stage process can balance the VFA, alkalinity, and methanogens in both reactors, thus, can increase the process stability and improve the digestion efficiency [13,15]. The specific objective of this research is to investigate a two-stage process to enhance the stability of one-stage anaerobic digestion of food waste, in addition to increase the digestion efficiency of horticultural waste and methane production in high-solid system, making the overall process more energy sustainable. The effects of the duration of the first stage and the ratio of food waste to horticultural waste on HSAD performances were investigated in a batch system. Finally, HSAD performances of two-stage process and one-stage codigestion were compared in a semi-continuous system. The outcome of this study will establish some fundamentals for the exploration of a novel technique of the potential improvement of HSAD of food waste and horticultural waste.

2. Materials and methods

2.1. Organic wastes and inoculum

Grass (*Axonopus compressus*) was collected from the yard of the National University of Singapore. The grass was shredded and homogenized to small pieces (approximately 2 cm in length for grass). The food waste, a mixture of noodle, rice and vegetables was first taken and was collected from a canteen of the National University of Singapore and non-biodegradable contaminants were removed. It was then homogenized using a macerating grinder and frozen at −20 °C. Before using the frozen feedstock, it was thawed and stored at 4 °C for no more than one week. The chicken manure was collected from the Chew's Group Limited, Singapore. A scraping system was used for manure collection, and the manure was then stacked in an open field. The anaerobic sludge from PUB Ulu Pandan Water Reclamation Plant was used as the inoculum. It had a pH of 7.62, total solids (TS) of 29.3 g/L and VS/TS of 73.12%. Finally, the sludge was centrifuged and the sludge cake was used as inoculum. The research was divided into: characterization of organic wastes and inoculum, high-anaerobic digestion of food waste, high-solid anaerobic digestion of grass, two-stage HSAD performance in batch system and two-stage HSAD performance in a semi-continuous system.

2.2. High-solid digestion of food waste

The high-solid codigestion of food waste and chicken manure was performed in triplicate in 250 mL reactors containing substrate of 5.0 g of VS. The VS ratio of inoculum to organic wastes was chosen as 1:4, which was used for biogas production [20]. The batches were incubated at different ratios of food waste, chicken manure and grass as, shown in Table 1. After inoculation, all batch reactors were purged with nitrogen gas to create an anaerobic condition. The digesters were then placed in a warm room at mesophilic temperature (35 ± 1 °C).

2.3. High-solid anaerobic digestion of grass

The effects of adding digestate on cumulative methane yield were tested using the digestate of Exp. 1 Batch 4 (shown in Table 1) as inoculum at 35 °C. The VS ratio of digestate to grass was controlled as 1:5, 2:5, 3:5, 4:5, marked as FCS1, FCS2, FCS3 and FCS4, respectively. The VS of grass was 5.0 g.

To compare the HSAD performance of two-stage process, codigestion of grass, FW and CM was carried out with initial TS as 20% and the substrate to inoculum ratio of 4.0 (based on VS) at 35 °C. The VS ratio of FW to CM to grass was 4:4:5 with C/N ratio as 17.11. The total VS of grass, food waste and chicken manure was 5.0 g.

2.4. Two-stage anaerobic digestion

The scheme of the two-stage digestion system is presented in Fig. 1. Codigestion of food waste and chicken manure was carried out in the first-stage digester. The digestate was then transferred to the second-stage and mixed with grass. If necessary, the effluent/residue produced in second-stage digester was recirculated back to the first-stage digester. Before pumping the liquid to the first-stage digester, the outlet of the second-stage digester was equipped with a sedimentation tank, to separate and settle the large particles. To optimize the two-stage process, the effects of VS ratio of food waste/grass and the duration of the first-stage on HSAD performances were tested. The effects of the first-stage duration on total biogas yield were studied with TS of 20%, food waste/chicken manure ratio of 4:5 (based on VS). The VS ratio of inoculum to organic wastes was chosen as 1:4. The first-stage duration was chosen as 1 day, 2 days, 4 days, 5 days and 7 days. With the same total organic wastes, the ratio of food waste to grass on digestion performance was tested with a first-stage duration of 3 days.

2.5. HSAD in semi-continuous system

The semi-continuous experiment was carried out according to the diagram shown in Fig. 1. The two-stage process was carried out with food waste, chicken manure and grass (with the ratio 3:5:5, based on VS) in 1000 mL bioreactor at 35 °C. Initial total VS was kept as 60.0 g. The VS ratio of inoculum to organic wastes was chosen as 1:4. The TS was kept as 20.0% by adding deionized water. The start-up period was 15 days and then initiated the semi-continuous style. Before being transferred to the 2nd stage, the mixture of food waste and chicken manure was treated with inoculum or digestate for 3 days. All reactors were gently mixed manually prior to sampling and feeding with OLR of 6.00 gVS/(L·day), 4.00 gVS/(L·day) and 2.00 gVS/(L·day). The semi-continuous process was divided into 4 stages: start-up, OLR1, OLR2 and OLR3. In the semi-continuous system, the duration for each stage is 30 days. To reduce the impact of changing organic loading rate, there was an internal of 15 days between each stage. As comparison, codigestion of the mixture of food waste, chicken manure and grass was carried out with the same OLRs.

2.6. Analytical methods

Total solids (TS) and volatile solids (VS) contents were analyzed according to the standard methods of the American Public Health Association [21]. Simultaneous determination of the carbon, hydrogen, nitrogen and sulphur (CHNS) contents in grass and food