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Performance enhancement of leaf vegetable waste in two-stage anaerobic systems under high organic loading rate: Role of recirculation and hydraulic retention time

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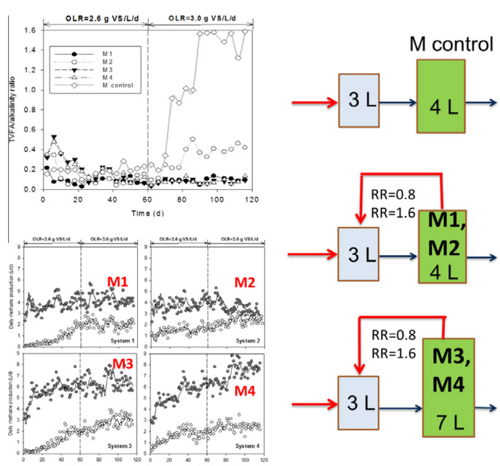
HIGHLIGHTS

- Limited hydrolysis under high loading rate resulted in process failure.
- Recirculation improves methane production under high loading rate.
- Short HRT under high recirculation rate caused instability of methanogenic reactor.
- Increased recirculation and retention time further improved overall performance.

GRAPHICAL ABSTRACT



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ABSTRACT

Continuous laboratory-scale experiments were conducted on two-stage anaerobic systems treating vegetable waste (VW) to improve CH_4 production. The acidogenic reactors were employed with a serial methanogenic reactor configuration with volume distribution ratios of 3 L/4 L and 3 L/7 L (acidogenic reactor/methanogenic reactor), as well as recirculation rates (RRs) of 0.8 and 1.6. Results showed that recirculation improved the performance of VW anaerobic digestion under an organic loading rate (OLR) of 2.6 g VS/L/d. The OLR increased from 2.6 g VS/L/d to 3.0 g VS/L/d to compare the stability of the processes and to study the behavior response of serial systems. System control without recirculation was susceptible to overloading and volatile fatty acids (VFAs) utilization was inhibited in the methanogenic reactor, which was implemented as a fixed-bed biofilm reactor with active carbon fiber textiles. These findings indicated overall process failure. The ratio of total volatile fatty acid (TVFA) and alkalinity gives a good indication of the process stability of anaerobic digestion. The TVFA/alkalinity ratio of the methanogenic reactor in the 3 L/4 L configuration, with RR of 1.6, increased to approximately 0.5, which

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indicates potential imminent failure of the methanogenic process. However, the methanogenic reactorin the 3 L/7 L configuration helped in utilizing the VFA produced by the overloading in the acidogenic reactor, which improved the CH_4 production and conversion efficiency of the system.

1. Introduction

China's economy has experienced a remarkable growth since economic reforms. This rapid economic growth in last three decades has led to energy consumption increased drastically. Crude oil consumption reached to be 467 million ton in 2012 according to National Bureau of Statistics of China [1]. China is highly dependent on oil importation, and thus energy security makes development of sustainable energy sources be a prerequisite for the sustainable economic development. The renewable energy production and energy dependency associated with fossil fuels have made anaerobic digestion of organic waste for production of biomethane to be an attractive option [2].

Vegetable waste (VW) is produced in large quantities in markets and vegetable-producing areas, thus constituting a source of decay, odor, which results in pollution of the environment when not properly treated. Anaerobic digestion cannot be only an efficient treatment, but also produce methane [3,4]. However, anaerobic digestion is often blocked in an acid crisis, in which the reaction rates of hydrolysis and acidogenesis substantially exceed that of methanogenesis [5]. Mata-Alvarez et al. [6] investigated the performance of a mesophilic single-stage digester for the treatment of a combination of fruit wastes and VWs. They found that the organic loading rate (OLR) was quite limited at less than 3 g volatile solid (VS)/L/d. The large and rapid production of volatile fatty acids (VFAs) highlighted the validity of this OLR limitation. Jiang et al. [7] concluded that a stable anaerobic digestion of VW at OLR of 3 g VS/L/d or higher may be unachievable without supplementation or the use of co-substrates.

Two-stage anaerobic digestion has been proposed by several researchers as a potential solution to improve the overall process efficiency and energy recovery over the traditional single-stage anaerobic digestion process. This approach has been widely used to treat easily biodegradable organic wastes, such as the waste from food, fruits, and vegetables [8,9]. Two-stage anaerobic digestion involves a process configuration employing separate reactors for acidification and methanogenesis connected in series, thus enabling the optimization of both processes [8]. The advantage of such system lies in the strong buffering capacity of the OLR in the first stage, which enables a constant feeding rate in the methanogenic stage. Thus, this approach presents a more stable operation and higher OLR treatment capacity than traditional single-stage anaerobic digestion [8–10]. However, the two-stage anaerobic digestion of organic waste involves the accumulation of metabolic intermediary products, such as VFA, in the acidogenic reactor. These accumulated VFAs reduce the local pH level and suppress microorganism/enzyme activity, thus degrading performance [11–13].

Investigations related to alleviating the inhibition of hydrolysis in the acidogenic reactor have mainly focused on the removal of VFA, including such processes as adsorption and dilution. The addition of certain adsorbents, such as activated carbon and clay minerals, into the acidogenic reactor reduces VFA concentration, but such materials are relatively costly [13]. Moreover, the addition of adsorbents relates to an approach for cleaning the contaminant residue and recovering the adsorbent material for reuse [14]. Implementing effluent recirculation is a viable option that has been used for various solid organic wastes. Recirculation can help alleviate VFA inhibition because of the effects of dilution and pH adjustment [15–17]. Moreover, recirculation enables proper sludge exchange for the diffusion and advection of VFA, as well as transfers excess VFA from the acidogenic reactor to the methanogenic reactor [18–20]. The reported recirculation strategy was applied to two-stage anaerobic digestion for the treatment of food waste [21], soybean meal waste [15], and sewage sludge [22].

Effluent recirculation is a promising process that elevates pH levels and improves acidogenic performance. Chen et al. [15] investigated a rotational drum fermentation system with methanogenic recirculation using fresh soybean meal as substrates. A first-order hydrolysis rate constant of 9.0×10^{-3}/d for the non-recirculation system at pH 4.5–4.6 and 15.8×10^{-3}/d for the recirculation system at pH 4.6–5.2 were obtained. The recirculation promoted the hydrolysis of the substrate, in which the apparent hydrolysis rate constant and VS degradation were higher than those of the non-recirculation system. In addition, the effluent from the methanogenic reactor contains an established microbial population and can accelerate waste degradation. Zhang et al. [23] observed that increasing RR can enhance hydrolysis because of the improved total extracellular enzyme activities. Effluent recirculation was achieved by recycling the effluent from the methanogenic to the acidogenic process, which not only alleviated the inhibition of excess VFA but also established a good condition for the process. Most results demonstrated that the effluent effectively retained neutral pH in the acidogenic reactor and reduced the external alkalinity addition. However, the effect of recirculation on the two-stage anaerobic digestion of VW under high OLRs remains unclear.

Hydraulic retention time (HRT) serves an important function in the performance and stability of anaerobic digestion [24]. A sufficiently long HRT is critical to maintain the slow and stable growth of methanogenic microorganisms in the digester. An increase in HRT is a potential method to improve the efficiency of methane

Table 1
Characteristics of raw vegetable waste and seed sludge for acidogenic/methanogenic reactors.

Parameter	Vegetable waste	Acidogenic reactor inoculum	Methanogenic reactor inoculum
TS	5.5 ± 0.5%	11.6 ± 0.5 g/L	7.3 ± 0.3 g/L
VS	4.8 ± 0.6%	7.2 ± 0.8 g/L	3.2 ± 0.2 g/L
pH	–	5.1 ± 0.1	7.6 ± 0.1
COD	1.6 ± 0.2 g/g TS	17.8 ± 1.3 g/L	2.1 ± 1.1 g/L

The values are expressed as average ± standard deviation.
TS: total solids.

Table 2
Operational characteristics of the two-stage anaerobic digesters.

Systems	Working volume of acidogenic reactor (L)	Working volume of methanogenic reactor (L)	Recirculation rate (RR)	Feed rate (L/d)
Control	3	4	0	0.5
1	3	4	0.8	0.5
2	3	4	1.6	0.5
3	3	7	0.8	0.5
4	3	7	1.6	0.5