



Innovative method for increased methane recovery from two-phase anaerobic digestion of food waste through reutilization of acidogenic off-gas in methanogenic reactor



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HIGHLIGHTS

- Two-phase AD with acidogenic gas diversion from LBR to UASB increased CH₄ recovery.
- Acidogenic gas diversion increased the COD by 27% and CH₄ recovery by 38.6%.
- Acidogenic gas utilization contributes ~8% increase in CH₄ recovery.
- Mixed acid fermentation dominated by butyrate was observed with gas diversion.

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ABSTRACT

In this study, the performance of a two-phase anaerobic digestion reactor treating food waste with the reutilization of acidogenic off-gas was investigated with the objective to improve the hydrogen availability for the methanogenic reactor. As a comparison a treatment without off-gas reutilization was also set up. Results showed that acidogenic off-gas utilization in the upflow anaerobic sludge blanket (UASB) reactor increased the methane recovery up to 38.6%. In addition, a 27% increase in the production of cumulative chemical oxygen demand (COD) together with an improved soluble microbial products recovery dominated by butyrate was observed in the acidogenic leach bed reactor (LBR) with off-gas reutilization. Of the increased methane recovery, ~8% was contributed by the utilization of acidogenic off-gas in UASB. Results indicated that utilization of acidogenic off-gas in methanogenic reactor is a viable technique for improving overall methane recovery.

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1. Introduction

Anaerobic digestion (AD) is an attractive waste treatment technology in which both waste disposal and energy recovery can be achieved. Two-phase AD is more efficient and stable than single phase AD and is gaining momentum recently (Selvam et al., 2010; Xu et al., 2014). With the separation of hydrolysis/acidogenesis from methanogenesis, two-phase AD facilitates specific enrichment of acidogens and methanogens (Azbar and Speece, 2001). Hydrogen (H₂) and carbon dioxide (CO₂) are the major components of acidogenic off-gas in the acidogenic reactor and their amounts could be increased with enhanced biodegradation

of organic wastes. Many reports focused on recovery of H₂ and/or methane from two-phase AD of organic wastes; however, the energy efficiencies were rarely compared. Harvesting H₂ or methane as sole product would incur the loss of the other, for example, recovery of acidogenic H₂ might lead to poor leachate quality for the subsequent methanogenesis; whereas, focusing on methane recovery in the second phase methanogenic reactor would lead to loss of energy carried by H₂. Considering the explosive nature of H₂ and the available infrastructure, methane gas is considered to be the viable energy form.

Hydrogen is produced during hydrolysis of organic matter (C₆H₁₀O₄) as well as acidogenic generation of butyrate and acetate. It was reported that H₂ production during acidogenesis of food waste can reach 0.9–1.8 mol-H₂/mol-hexose with a maximum H₂ volume content of 69% (Shin et al., 2004). It is estimated that the energy carried by H₂ during acidogenesis can be up to 30% of the overall energy recovered (Clark et al., 2012). Therefore, it is

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attractive and profitable to harness this part of energy. There are three potential solutions for this problem: (1) reduce the production of H₂ in the acidogenic reactor; (2) utilization of H₂ and simultaneously reduce CO₂ to acetate by homoacetogens in a coupling system (Nie et al., 2007, 2008); and (3) utilization of H₂ and CO₂ in the methanogenic reactor through hydrogenotrophic methanogenesis. Supplementation of H₂ to methanogenic reactor enhanced the methane recovery (Luo and Angelidaki, 2013a,b). The first approach appears not realistic due to the fact that usually less H₂ generation would be accompanied by lower degradation rate of the organic substrates and hence would decrease the overall conversion efficiency. Nie et al. (2007) reported the utilization of H₂ in a coupled reactor through homoacetogenesis and achieved 52% increase in acetate production. However, integrating one more reactor would increase the economic input and operational complexity of the AD process. Due to the highly thermodynamically favorable nature of hydrogenotrophic methanogenesis, utilization of H₂ in methanogenic reactor, thus, would be a desirable choice.

Hydrogen and CO₂ are the by-products of acidogenesis of organic compounds through different metabolic pathways, i.e., ethanol, propionic and butyric-type fermentations. Ren et al. (2007) had observed that a mixed consortia fermentation often associates with more than one soluble product (acetate, propionate, etc.). During anaerobic acidogenesis, H₂ often accumulates in the headspace of the reactor and hence blocks further degradation of acids that result in H₂ evolution (Miron et al., 2000) through direct inhibition of the hydrogenase reaction (Kongjan et al., 2014). Besides, the H₂ partial pressure may influence the yields of the main metabolic products i.e. acetate and ethanol (Collet et al., 2005). Even though the biological function of H₂ production is still not completely understood yet, H₂ seems to be more than just an intermediate product during acidogenic fermentation but is suspected to be the controlling factor regulating the anaerobic metabolic pathways. Nevertheless, there was no investigation in literature regarding the changes of metabolic pathways when the acidogenic off-gas is continuously diverted to methanogenic reactor.

In this study, diversion of acidogenic off-gas from acidogenic leach bed reactor (LBR) to methanogenic upflow anaerobic sludge blanket (UASB) for utilization of H₂ and CO₂ via direct hydrogenotrophic methanogenesis was investigated as a strategy for improving overall energy recovery from two phase AD of food waste. Supplementation of H₂ to methanogenic reactor could enhance methane gas generation and upgrade CH₄ content in the mixed biogas (Luo and Angelidaki, 2013a,b). General performance of the two-phase AD system, shift of acidogenic metabolic pathway and overall CH₄ recovery under the configuration of acidogenic off-gas diversion to the methanogenic reactor were investigated to evaluate the feasibility and efficiency of this strategy.

2. Materials and methods

2.1. Substrate and inoculum

Simulated food waste and anaerobically digested sludge as reported by Yan et al. (2014) were used as substrate and inoculum, respectively. The seed sludge was stored in cold room (4 °C) prior to use. The selected physicochemical properties of the simulated food waste and AD sludge are presented in Table 1.

2.2. Experimental set up

Four identical LBRs (LBR-gas and LBR-control) were made from 150 mm diameter steel pipe, which was capped at both ends to form a closed vessel with a 5.4 L working volume and 2.9 L

Table 1
Characteristics of food waste and inoculum.

Parameter	Food waste	Sludge
Total solids (TS, %)	40.0 ± 2.5	4.6 ± 0.1
Volatile solids (VS/TS, %)	98.0 ± 0.1	89.7 ± 0.0
Total organic carbon (TOC, %)	45.9 ± 4.4	8.5 ± 0.0
Total Kjeldahl nitrogen (TKN, g/kg)	28.8 ± 0.5	2.0 ± 0.0
Carbohydrate (%)	74.0 ± 2.0	ND ^a
Lipid (%)	10.0 ± 0.5	ND
Protein (%)	18.0 ± 0.2	ND

^a Not determined.

leachate storage volume. A stainless steel mesh was placed on the bottom of the reactor above the leachate storage chamber (Selvam et al., 2010) to support the food waste and a layer of glass beads was placed underneath to prevent clogging as well as solids entering into the leachate. The percolation and filtration occurred naturally. One of the two gas outlets at the top of the LBR was connected to the bottom inlet of UASB reactor through a peristaltic pump. Four UASB (UASB-gas and UASB-control in duplicates) reactors with 10 L working volume each were used as the second phase methanogenic reactors.

Simulated food waste, 2.0 kg, was mixed with 20% (1/S, wet basis) AD sludge as inoculum and 10% (v/v) wood chips as bulking agent according to a previous study (Xu et al., 2012). The liquid to solid ratio during this experiment was kept at 1.0 (Xu et al., 2014), which means 2.0 L of tap water was loaded to each LBR. One-day sampling frequency was chosen to avoid acid crisis. During each sampling, the leachate was taken out and its volume was recorded, then exactly 50% of the leachate was returned back to the LBR from the top after adjusting the pH to 6.0 using 0.5 M NaHCO₃. The remaining 50% of the leachate was fed to corresponding UASBs of which 50 mL was sampled for the analysis of chemical oxygen demand (COD), volatile fatty acids (VFAs), and pH. The biogas compositions were analyzed every day to evaluate the performance of these systems.

2.3. Diversion of acidogenic off-gas to UASB

Biogas produced in acidogenic LBR mainly contains H₂ and CO₂, direct precursors for the hydrogenotrophic methanogenesis. To assess the efficiency of acidogenic off-gas diversion from LBR to UASB on the methane recovery, LBR off-gas diversion to UASB (UASB-gas) as the test and LBR-control coupled with UASB-control without off-gas diversion as control were designed (Fig. S1). The flow rate of off-gas diversion was set at 1.5 L/L-reactor.

In order to compare the effect of acidogenic off-gas diversion on the solubilization of particulate solids and the hydrolysis rate of monomers to short-chain molecules, kinetics of production of COD and soluble products were determined. First-order kinetics were used to evaluate the hydrolysis rate of food waste in LBR under different treatments. The effects of different operations on the performance of hydrolysis have traditionally been simplified to the first-order kinetics (Vavilin et al., 2008). In the first-order kinetics,

$$\frac{dS}{dt} = -kS \quad (1)$$

$$\frac{dP}{dt} = \partial kS \quad (2)$$

S is the volatile solids (VS, kg) concentration of particular substrates, *P* represents concentration of soluble products (SP, g), *k* is the first-order hydrolysis constant (d⁻¹), and ∂ (g SP/kg VS) is the conversion

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