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Construction and evaluation of efficient solid-state anaerobic digestion system via vinegar residue

Yunlong Zhou[a,b], Zhiyang Xu[a,b], Mingxing Zhao[a,b], Wansheng Shi[a,b], Zhenxing Huang[a,b], Di He[a,b], Wenquan Ruan[a,b,*]

[a] School of Environment and Civil Engineering, Jiangnan University, Wuxi 214122, China
[b] Jiangsu Key Laboratory of Anaerobic Biotechnology, Wuxi 214122, China

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ABSTRACT

Anaerobic digestion is a feasible method for vinegar residue disposal. However, its treatment efficiency is limited significantly by the low degradation of lignocellulose. In this study, a stable and efficient anaerobic digestion system for vinegar residue was constructed. The continuous solid-state reactor achieved a specific production of 418 mL·g-1 VS biogas and 223 mL·g-1 VS methane at a high organic loading rate (OLR) of 5.83 g_{VS}·$(L·d)^{-1}$. The stable degradation of lignocellulose between 39.5% and 36.4% was key factor for stable anaerobic digestion at high OLR. This stability under optimum OLR was due to the increase in the degradation of hemicellulose, which compensated for the loss of lignocellulose degradation. The enrichment of microorganism related to lignocellulose hydrolysis and the stable microbial community structure ensured efficient anaerobic digestion under high OLR condition. Digestion efficiency can be further improved mainly by increasing cellulose degradation. This investigation provided the theoretical basis for practical application of this digestion system for solid vinegar residue treatment.

1. Introduction

Vinegar residue contains vinegar fermentation by-products and additives such as bran and rice husk (Feng et al., 2013). The production of approximately 3 million tons per year in China generates about 3.2 million tons vinegar residue (Feng et al., 2017). Environmentally safe disposal of production residues is, therefore, a major focus of the vinegar industry.

Traditional methods of disposing vinegar residue include as fodder, as a substrate in edible fungus cultivation and for soilless plants cultivation (Song et al., 2013, 2014). Disadvantages of these disposal methods include low degradation efficiency, limited treatment capacity and insufficient economic value.

Anaerobic digestion is an efficient method of organic wastes treatment (Paudel et al., 2017; Ratanatamskul and Manpetch, 2016; Zhang et al., 2017). On the one hand, complex macromolecular organic matters can be degraded efficiently by hydrolysis, acidification, and methanogenesis (Liu et al., 2015). On the other hand, residues of anaerobic digestion are rich in nitrogen and phosphorus, which can be used for agricultural production as organic fertilizers (Baba et al., 2013). However, the digestion efficiency of vinegar residue is limited by the low degradation rate of lignocellulose (He et al., 2013). Different pretreatments, such as acid, alkali, steam, and biological treatments have been tested on vinegar residue to enhance the utilization of lignocellulose (Feng et al., 2016; Shen et al., 2017; Wang et al., 2015). Although the hydrolysis efficiency is increased, many disadvantages, such as increasing running cost, byproduct-poisoning of the anaerobic digestion system, and secondary pollution, are encountered when pretreatments are used (Jain et al., 2015). Directly utilizing vinegar residue was attempted to test its biochemical methane potential in liquid system. However, the liquid digestive system (total solid [TS] < 10%) is not suitable for treating vinegar residue because the lignocellulosic component accumulates at the surface (Kim and Oh, 2011) decreasing the contact between substrate and bacteria, thereby limiting the digestion efficiency. In addition, excessive energy consumption and biogas slurry production both increase due to the addition of large amounts of external water (Feng et al., 2013, 2017; Li et al., 2015). In contrast, TS content in solid-state anaerobic digestion is generally above 15%, which is more suitable for the digestion of lignocellulosic biomass (Li et al., 2011; Yang et al., 2015a). Compared to liquid anaerobic digestion, solid-state anaerobic digestion has several advantages, such as higher volumetric methane productivity, reduced energy requirements for heating, less wastewater generation, and a low-moisture digestate that is easier to handle. To date, few studies have

* Corresponding author. School of Environment and Civil Engineering, Jiang Nan University, 1800 Lihu Avenue, Wuxi, Jiangsu Province, China.
E-mail address: wqruanjn@gmail.com (W. Ruan).

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Table 1
The characteristic of substrate and inoculum.

Parameter	Vinegar residue	Inoculum
Total solids (%)[a]	32.80 ± 0.76	14.69 ± 0.12
Volatile solids (%)[a]	31.07 ± 0.24	7.17 ± 0.36
VS/TS (%)	94.73 ± 0.72	48.81 ± 1.03
C (%)[b]	49.12 ± 1.04	46.87 ± 0.38
H (%)[b]	5.97 ± 0.05	6.42 ± 0.16
N (%)[b]	1.71 ± 0.02	2.47 ± 0.05
S (%)[b]	0.15 ± 0.01	0.33 ± 0.02
C/N	28.68 ± 0.59	19.01 ± 0.74
Protein (%)[b]	9.98 ± 0.42	NA
Cellulose (%)[b]	25.29 ± 0.82	NA
Hemicellulose (%)[b]	21.24 ± 0.21	NA
Lignin (%)[b]	16.81 ± 0.08	NA

± : standard deviations. NA: not analyzed. [a]: as total weight of sample. [b]: as total solid of sample.

explored the microbial community dynamics during different stages of vinegar residue anaerobic digestion or have attempted to relate microbial diversity with metabolic function.

The objectives of this study are as follows: (1) to construct a stable and efficient anaerobic digestion system by using vinegar residue running through a continuous solid-state reactor; (2) to evaluate the degradation and transformation of vinegar residue under different organic loading rates (OLRs); (3) to investigate the key factors that keep the anaerobic digestion system efficient; (4) to analyze the effect of microbial community succession on the metabolism of substrates.

2. Materials and methods

2.1. Substrate and inoculum

Anaerobic digester effluent from a single-phase mesophilic anaerobic digestion of food waste was used as inoculum. The anaerobic digestion substrate was vinegar residue from vinegar production enterprises and mainly included rice husk and vinegar raw material residue, which accounted for 6.83% of the dissolved material. The main parameters of substrate and inoculum are shown in Table 1.

2.2. Experimental setup and operating conditions

A full-mixed reactor with 8L working volume was used in the experiment (Fig. 1). The vinegar residue was fed from the feed inlet at the top of the reactor during digestion. During the operation of the reactor, the substrate and inoculum were completely mixed and uniformly distributed, and the digestion activity was spread throughout the reactor. The digestion activity enhances the hydrolysis efficiency of the substrate and promotes the degradation and methane conversion of the substrate through the synergistic action of the hydrolyzing microorganisms and methanogens. The biogas produced during digestion was exported from the outlet of the upper part of the reactor. A biogas flow meter (LMF-1, China) was connected on the reactor to measure the daily biogas produced. The biogas was stored in the gasbag for gas composition analysis. The digestate was discharged through the outlet at the bottom of the reactor. After solid–liquid separation, the slurry was recirculated back into the reactor. Separation of the solids from the liquid was required because complete full recirculation of bioreactor effluent could lead to the accumulation of ammonia nitrogen, which can severely inhibit anaerobic digestion. Therefore, the reflux ratio was regulated during operation to alleviate ammonia nitrogen accumulation. In the experiment, the temperature was maintained at 37 ± 1 °C, and the stirring rate was adjusted through the control cabinet.

For startup, the reactor was loaded with inoculum to the working volume and was pre-incubated to eliminate all residual substrates. In the adaptation period, a small amount (10 g) of vinegar residue was added to the reactor. Anaerobic digestion was then conducted to achieve stabilized conditions for digestion and biogas production. After startup and adaptation period, the continuous loading phase of the reactor was begun.

Experiments were performed in five stages by gradually increasing the OLR. The operation parameters of each stage are shown in Table 2. During the operation, the TS content of the system was maintained at 15%–18%.

2.3. Chemical analyses

Total solid (TS) and volatile solid (VS) were determined according to the standard methods (APHA et al., 2005). Elemental compositions (C, H, N, and S) were measured by an elemental analyzer (Elementar, Germany). Protein was estimated by multiplying the total Kjeldahl nitrogen by 6.25, and the total Kjeldahl nitrogen was measured by Kjeldahl method (Hall and Schonfeldt, 2013). Volatile fatty acids (VFA) were determined by the colorimetric method (Ren and Wang, 2004), Total ammonia nitrogen (TAN) was determined by the Nessler's reagent method (Dave et al., 2017), and the pH value was determined by a Mettler-Toledo Delta320 pH meter. The biogas composition was analyzed by portable gas analyzer (GAS-BOARD 3200L, China) (Abdelsalam et al., 2017). The cellulase activity was determined by DNS method (Lowe et al., 1987) using sodium carboxymethyl cellulose

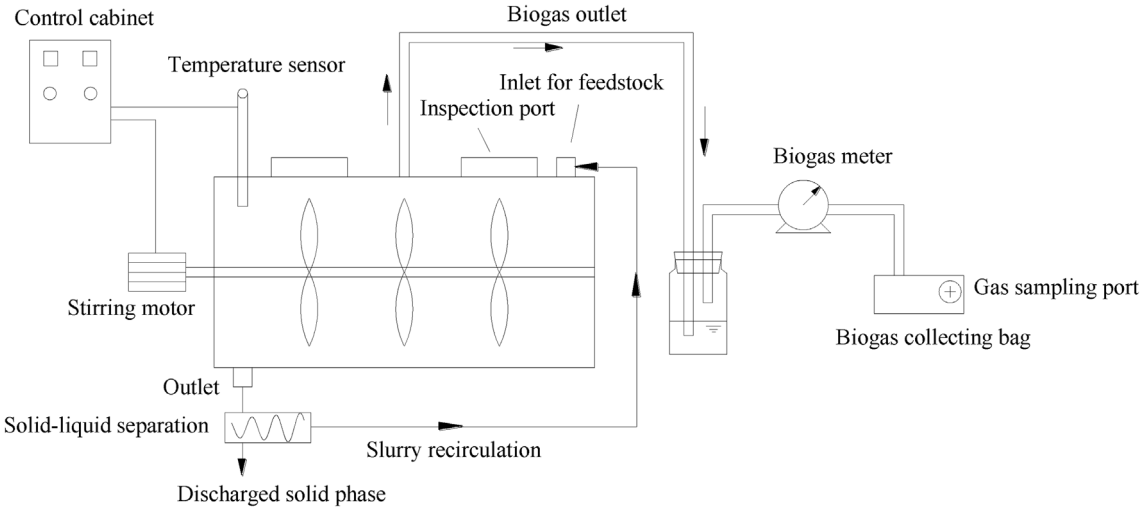

Fig. 1. Vinegar residue solid-state anaerobic digestion reactor.