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A half-submerged integrated two-phase anaerobic reactor for agricultural solid waste codigestion

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ABSTRACT

Anaerobic digestion is widely used in bioenergy recovery from waste. In this study, a half-submerged, integrated, two-phase anaerobic reactor consisting of a top roller acting as an acidogenic unit and a recycling bottom reactor acting as a methanogenic unit was developed for the codigestion of wheat straw (WS) and fruit/vegetable waste (FVW). The reactor was operated for 21 batches (nearly 300 d). Anaerobic granular sludge was inoculated into the methanogenic unit. The residence time for the mixed waste was maintained as 10 d when the operation stabilized, and the temperature was kept at 35 °C. The highest organic loading rate was 1.37 kg VS/(m^3 d), and the maximum daily biogas production was 328 L/d. Volatile solid removal efficiencies exceeded 85%. WS digestion could be confirmed, and efficiency was affected by both the ratio of WS to FVW and the loading rate. The dominant bacteria were *Bacteroides*-like species, which are involved in glycan and cellulose decomposition. Methanogenic community structures, pH levels, and volatile fatty acid concentrations in the acidogenic and methanogenic units differed, indicating successful phase separation. This novel reactor can improve the mass transfer and microbial cooperation between acidogenic and methanogenic units and can efficiently and steady codigest solid waste.

1. Introduction

Anaerobic digestion is an efficient and sustainable technology that has been widely used in agricultural waste treatment [1–3]. The biogas produced during anaerobic digestion is a renewable energy, and the liquid and solid residues can be used as green fertilizers. However, the anaerobic digestion of agricultural wastes with high solid concentrations is limited by low hydrolysis rates [particularly for lignocellulosic waste such as wheat straw (WS)], low mass-transfer efficiency, and difficulty in microbial biomass reservation [4]. Anaerobic microecosystem balance is also readily disrupted because of the different growth rates and optimal conditions of hydrolytic and fermentative bacteria and methanogens [5].

Aiming to the problem of high solid anaerobic digestion, codigestion was suggested and investigated. Lignocellulosic waste can be digested simultaneously with other materials, such as manure, sludge, and vegetable and fruit waste, in order to adjust the C/N ratios of the raw materials and improve mass transfer [6,7]. Two types of reactor configurations, namely, single- and two-phase reaction systems, were developed for solid agricultural waste codigestion. Single-phase reactors can be operated in batch, semi-batch, or continuous modes. The continuously stirred tank reactor (CSTR) is a typical single-phase anaerobic reaction system in which hydrolytic and fermentative bacteria and methanogens are mixed in a single reaction zone [8]. With the development of high-rate anaerobic reactors, such as upflow anaerobic sludge bed (UASB), for liquid materials, biomass preservation, high methanogenic reaction rates, and high mass-transfer efficiency can be achieved by granular sludge and up-flow. However, hydrolysis limits the application of high-rate reactors to high solid anaerobic digestion, particularly for agricultural waste such as lignocellulose [9].

Meanwhile, two-phase anaerobic digestion has the advantage of operational stability and high-solid digestion efficiency [10,11]. Two-phase digestion systems spatially separate the acidification phase from the methane production phase using two separated bioreactors in series. This configuration allows the efficient hydrolysis of solid materials while maintaining favorable

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Nomenclature and abbreviations

C	carbon
CSTR	continuously stirred tank reactor
EGSB	expanded granular sludge bed
FVW	fruit/vegetable waste
HIT	half-submerged integrated two-phase
LB	Luria-Bertani
N	nitrogen
PCR	polymerase chain reaction
PMMA	polymethyl methacrylate
SLBR	sequencing leach bed reactor
SEM	scanning electron microscopy
TC	total carbon
TOC	total organic carbon
TS	total solid
UASB	upflow anaerobic sludge bed
UASS	upflow anaerobic solid-state
VFAs	volatile fatty acids
VS	volatile solid
WS	wheat straw

methane production. Reactor configuration is a major concern in related studies. For example, an upflow anaerobic solid-state (UASS) reactor has been developed for the codigestion of agricultural waste [9]. A number of researchers combined an initial digester with a UASB to digest crops or grass [12,13]. The sequencing leach bed reactor (SLBR) and CSTR coupled with a UASB are both considered promising [14]. Different types of two-phase anaerobic digesters, including integrated systems, have been effectively applied to agricultural waste codigestion [15,16].

In this study, a novel reactor configuration, namely, the half-submerged, integrated, two-phase anaerobic reactor (HIT anaerobic reactor), was developed. The integrated reactor was based on the principle of combining separated acidogenic and methanogenic units as well as solid and liquid phases in one single reactor configuration, by using a half-submerged structure. The study aims to accelerate the hydrolysis of solid materials and enhance the mass transfer and syntrophic cooperation between acidogenic and methanogenic microorganisms. Experiments on WS and fruit/vegetable waste (FVW) codigestion were performed to test the effectiveness of the HIT anaerobic reactor. The objectives of the research are as follows: (1) to introduce the design concept and operational approach of the proposed HIT anaerobic reactor; (2) to evaluate the agricultural solid waste codigestion performance of the proposed reactor in terms of volatile solid (VS) removal and biogas production; and (3) to investigate the phase separation by comparing the pH levels, volatile fatty acid (VFA) concentrations, and microbial communities in both acidogenic and methanogenic units.

2. Materials and methods

2.1. Characteristics of WS and FVW

In this study, WS and FVW served as the main substrates. WS was collected from a farmland near Beijing, China. FVW, including pears, apples, bananas, watermelons, Chinese cabbage, and lettuce, was obtained from the waste dump of a fruit and vegetable market in Beijing. Both WS and FVW were shredded and homogenized to small pieces (approximately 5 cm in length) after the fruit cores were removed. Composition characteristics, such as total solid (TS) and VS, were analyzed; the results are shown in Table 1. The C/N ratio of WS is 49.67, whereas that of FVW is 15.62. These values indicate that nitrogen is insufficient when WS alone is used as the anaerobic digestion feedstock. Certain proportions of WS and FVW are required to improve the C/N balance. In this study, the C/N ratios in the range of 15.62–26.42 were investigated by adjusting the proportions of WS and FVW.

2.2. HIT anaerobic reactor design

The proposed innovative HIT anaerobic reactor in this study mainly consists of two parts, namely, the acidogenic unit on top and the methanogenic unit at the bottom. The entire apparatus and operation approach (Chinese patent: CN201010576176) are shown in Fig. 1. The reactor was composed of polymethyl methacrylate (PMMA) and stainless steel. A stainless steel roller that could be rotated at rates of 3–30 rpm was installed on top. Three inner clapboards separated the roll into six equal parts to ensure thorough mixing of the solid waste. Holes with 5 mm diameters were evenly distributed on the roller surface. The solid materials fed into the reactor were half-submerged in the liquid zone to allow sufficient transfer of the substance. A cuboid reactor with a hot water jacket composed of PMMA served as the methanogenic unit for the granular sludge cultivation and anaerobic reaction. A recycling system was installed between the acidogenic and methanogenic units to pump the hydrolysates from the acidogenic zone into the methanogenic zone. This process efficiently prevented acid accumulation and enhanced mass transfer. The biogas released from the reaction zones was collected from the top of the reactor. After the reaction, the solid residue and the additional water from raw materials were obtained from the roller and the liquid outlet, respectively, for further analysis. Half-submergence enhances organic waste dissolution and hydrolysis, which is rapidly activated by microorganism retention. The acidogenic and methanogenic zones can be separated in a combined reactor but can also be combined via mass transfer to achieve efficient anaerobic digestion.

In the current study, the efficient reaction volume of the reactor was 75 L, of which the acidogenic unit roller accounted for 25 L, whereas the methanogenic unit cuboid reactor accounted for 50 L. However, the volume of the methanogenic unit cuboid reactor could be reduced to approximately 25 L based on the operational performance observed in this study. This volume reduction can further improve the utilization efficiency and loading rate of the reactor.

2.3. Experiment design and parameters of the HIT anaerobic reactor

Experiments were conducted on 21 batches throughout an operation period of nearly 300 d. First, anaerobic granular sludge from a full-scale UASB reactor (obtained from Shandong Province, China) that treats starch wastewater was inoculated into the methanogenic unit at 35 °C. The sludge concentration in the methanogenic unit was approximately 20 g VS/L. The residence time for the mixed waste in the acidogenic unit decreased from 24 d to 17 d for the first four batches (considered as start-up periods) and was then maintained at 10 d for the subsequent batches. The WS/FVW ratios of the different batches ranged from 0.2 to 1.5 (as calculated form the VS amount), except that of the 15th batch, in which FVW was the sole feedstock. The roller rotating speed, inner recycling flow, and reactor temperature were maintained at 5 rpm, 0.45 m^3/h, and 35 °C, respectively, throughout the experimental period. The TS and VS of the raw materials and residues were respectively determined at the beginning and the end of each batch operation. The volume and total organic carbon (TOC) of the water discharged at the end of each batch operation were also measured. pH levels and VFAs were determined by daily sampling, and