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Serial completely stirred tank reactors for improving biogas production and substance degradation during anaerobic digestion of corn stover

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HIGHLIGHTS

- Serial configurations for anaerobic digestion of corn stover were conducted.
- Methane yield obtained from serial systems was 8.3–14.6% higher than single system.
- Serial systems improve substance conversion and more stable in process performance.
- HRT30 + 10 d serial system shows best methane production and conversions.

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ABSTRACT

Several completely stirred tank reactors (CSTR) connected in series for anaerobic digestion of corn stover were investigated in laboratory scale. Serial anaerobic digestion systems operated at a total HRT of 40 days, and distribution of HRT are 10 + 30 days (HRT10 + 30 d), 20 + 20 days (HRT20 + 20 d), and 30 + 10 days (HRT30 + 10 d) were compared to a conventional one-step CSTR at the same HRT of 40 d. The results showed that in HRT10 + 30 d serial system, the process became very unstable at organic load of 50 gTS·L^{-1}. The HRT20 + 20 d and HRT30 + 10 d serial systems improved methane production by 8.3–14.6% compared to the one-step system in all loads of 50, 70, 90 gTS·L^{-1}. The conversion rates of total solid, cellulose, and hemicellulose were increased in serial anaerobic digestion systems compared to single system. The serial systems showed more stable process performance in high organic load. HRT30 + 10 d system showed the best biogas production and conversions among all systems.

1. Introduction

Energy recovery from biomass is one of the major options to reduce greenhouse gases emissions and depletion of fossil fuels (Liu et al., 2015). In China, 165 million hectares of crops were cultivated in 2015 (Ning et al., 2016), and approximately half of the crop straws produced remain unused annually, causing serious air pollution and fire disaster due to open-field burning (Zheng et al., 2009a). Anaerobic digestion (AD) of crop straws into biogas via a consortia of bacteria has attracted increasing attentions recently as it could produce clean bioenergy, meanwhile, reduce waste discharge and pollution (Wang et al., 2017).

A number of digesters are being applied for AD process in both laboratory study and industrial project, completely stirred tank reactor (CSTR) is one of most commonly used for the anaerobic digestion of high-solid wastes such as straws (Maclellan et al., 2013; Seppälä et al., 2013). A single CSTR is simple to operate but less efficient in feedstock digestion and biogas production due to the "short-circuit". "Short-circuit" is a time frame when fraction of organic material in the feedstock remains in the reactor for shorter duration than the nominal retention time (Boe and Angelidaki, 2009), which is the major drawback associated with CSTR. For instant, for a single CSTR with a HRT of 40 d, the digestate discharged each day actually is a mixture of well digested and partially digested due to different times of feeding and staying in the digester. The mixture contains the feedstock fed up to 40 days ago and thereby well digested, and the feedstock fed down to yesterday (short-circuit) and digested very little. This would lead to lower bioconversion rate of digestible feedstock and lower biogas yield.

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Connecting two reactors in series (serial digestion) is an appropriate way to overcome the problems from single CSTR to increase the biodegradation rate as well as obtain more biogas production. Several studies have emphasized the feasibility of serial digestion. Boe (2006) demonstrated that CSTR serial digestion with percent volume distributions of 90/10% and 80/20% between the two stage methanogenic reactors treating sewage sludge improved biogas production by 11% compared to a traditional one-step CSTR. Another study reported that when CSTRs of sewage sludge connected in series with total working volume distributed as 70/30%, 50/50%, 30/70% or 13/87% between the two methanogenic reactors, the serial digestion at 70/30% and 50/50% volume distribution produced 13–17.8% more biogas and methane than the single CSTR process. However, 30/70% and 13/87% volume distribution reactors were noticed unstable (Kaparaju et al., 2009). This result was consistent with Boe (2006). Athanasoulia et al. (2012) carried out both single and serial systems to digest waste activated sludge at retention time of 12.3 and 19.7 days, and the results showed that the serial configuration improved biogas production by 9.5–40.1%.

It has been reported that the serial digestion also increased conversion of substrates (Athanasoulia et al., 2012). However, the material characteristics of high-percentage of lignocellulose and lower biodegradation rate of crop straw is totally different from the feedstock which have been widely studied by other researchers, because the complicated structural resistance from lignocellulose affects the hydrolysis efficiency of crop straw (Ziganshin et al., 2016). Applying serial anaerobic digestion using crop straw as raw material was not mentioned in literatures. Moreover, most literatures focused on arranging serial digestion system with a distribution of volume, and when it comes to the transformation of an existing plant with several same-sized reactors, structuring serial digestion with a distribution of HRT is also feasible.

The main objective of this study was to investigate the configuration of two-stage serial CSTRs anaerobic digestion systems for corn stover, and the effect of reactor configuration on biogas production and methane content from first and second stage of the serial systems. Besides, to improve the biodegradation rate of corn stover through serial systems, and at the same time to maintain process stability. In the serial systems, the first-stage reactors were applied as main bioconversion reactors, and the second-stage reactors as a recovery stage for further biodegradation of the effluent. All results from serial systems were compared to those obtained from a single-stage CSTR system operated on the same conditions.

2. Materials and methods

2.1. Feedstock and inoculum

The sample corn stover used in this study was collected from Shunyi District, Beijing. The harvested corn stover was air-dried in the open area, cut into 3–4 cm in length with a chopper, then ground to the size of 20-mesh by a hammer mill (YSW-180, Yanshan Zhengde Co, Beijing, China) and stored in laboratory at room temperature. Before fed into reactors, the corn stover was pretreated with NaOH solution based on the ratio of dry weight of corn stover: NaOH: H_2O = 10:0.2:60 (w/w/w) at ambient temperature (20 ± 2 °C) for three days. The wet state NaOH pretreatment method was advanced to pretreat corn stover, which is a cost-effective and highly efficient method for biological conversion (Zheng et al., 2009b).

The inoculum was collected from continuously operated stable biogas plant in Shunyi District, Beijing, China. The main characteristics of corn stover and the inoculum are listed in Table 1.

Table 1
Characteristics of materials and inoculum.[*]

Items	Corn stover	Inoculum
TS(%)[a]	94.7 ± 0.07	11.45 ± 0.05
VS(%)[a]	88.04 ± 0.18	5.99 ± 0.03
MLSS($g·L^{-1}$)[a]	–	107.00 ± 4.00
TC(%)[b]	43.21 ± 0.54	29.20 ± 1.14
TN(%)[b]	1.23 ± 0.08	2.60 ± 0.14
C/N(%)[b]	35.13 ± 0.29	11.28 ± 0.53
S(%)[b]	0.24 ± 0.07	0.69 ± 0.02
Cellulose(%)[b]	35.74 ± 0.83	–
Hemicellulose(%)[b]	27.82 ± 0.51	–
Lignin(%)[b]	4.21 ± 0.05	–

[*] Values are means ± SD (n = 3).
[a] Content of fresh matter.
[b] Content of dry matter.

2.2. Reactors set-up and operations

CSTR with a total volume of 10 L and a working volume of 8L was applied for anaerobic digestion. The top plate supported the mixer, mixer motor, temperature measuring port, while the feed tube and effluent tube were fit on upper side wall. Stable reactor temperature was maintained at 35 ± 1 °C by pumping hot water from an electrically heated thermostatic water bath to water jacket between the reactor walls.

Each reactor was set up with corn stover at 50 $gTS·L^{-1}$ and inoculum at mixed liquid suspended solids (MLSS) of 15 $g·L^{-1}$, based on the procedure from Hu et al. (2014). Reactors were stirred by mechanical mixers operated at a speed of 80 rpm for 10 min every 2 h.

After 30 days of adaption period, the reactors were considered ready for semi-continuous feed. Single CSTR system and first-stage reactors of serial systems were fed with NaOH pretreated corn stover, second-stage reactors of serial systems were fed directly with the effluent of their first-stages. The structural parts of the CSTR used and the serial system design are shown in Fig. 1. The HRT of first and second stage reactors varied based on the design of this study. The initial feeding organic loading rate (OLR) of the systems was 50 $gTS·L^{-1}$, and when the reactors reached a steady state, OLR was changed into 70 $gTS·L^{-1}$, and then 90 $gTS·L^{-1}$. The steady state was defined to be the point when biogas production rates varied within 5% of their average values after an operating time to more than one HRT period (Mulat et al., 2015). The used CSTRs were assumed as ideal CSTR, and when transferring effluent from first to second stage, the effluent was equally and equably distributed without any leakage. The first stage of HRT10 + 30 d contained 1 reactor (HRT10 + 30 d-I) and was operated at a HRT of 10 days, and the second stage (HRT10 + 30 d-II) contained 3 reactors at 30 days, which were operated entirely at the same conditions, and almost similar biogas production, methane content, substrate removal rate and process stability, so one of the three reactors was taken as example in tables, figures, and analysis. The first and second stages of HRT20 + 20 d serial digestion, both contained 1 reactor and were operated at a HRT of 20 d where the first stage was named HRT20 + 20 d-I and the second was HRT20 + 20 d-II. HRT30 + 10 d serial digestion took 3 reactors in first stage (HRT30 + 10 d-I) and 1 in the second stage (HRT30 + 10 d-II), and the three first stage reactors were paralleled and one taken as an example.

2.3. Analytic methods

Total solid (TS), volatile solids (VS) and MLSS of corn stover, inoculum and their mixture were determined according to the APHA standard methods (APHA, 1998). The total carbon (TC) and