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Minimizing mixing intensity to improve the performance of rice straw anaerobic digestion via enhanced development of microbe-substrate aggregates

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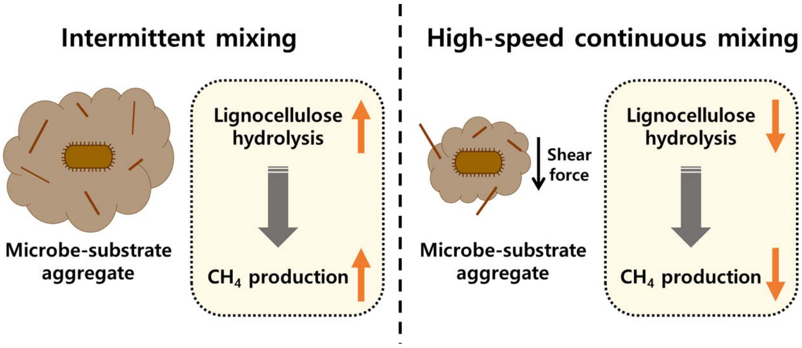
GRAPHICAL ABSTRACT



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ABSTRACT

The aim of this work was to study the effect of the differential development of microbe-substrate aggregates at different mixing intensities on the performance of anaerobic digestion of rice straw. Batch and semi-continuous reactors were operated for up to 50 and 300 days, respectively, under different mixing intensities. In both batch and semi-continuous reactors, minimal mixing conditions exhibited maximum methane production and lignocellulose biodegradability, which both had strong correlations with the development of microbe-substrate aggregates. The results implied that the aggregated microorganisms on the particulate substrate played a key role in rice straw hydrolysis, determining the performance of anaerobic digestion. Increasing the mixing speed from 50 to 150 rpm significantly reduced the methane production rate by disintegrating the microbe-substrate aggregates in the semi-continuous reactor. A temporary stress of high-speed mixing fundamentally affected the microbial communities, increasing the possibility of chronic reactor failure.

1. Introduction

Immense amounts of agricultural by-products such as rice straw, rice husk, wheat straw, corn stover, and fruit branch are produced worldwide every year (Kadam et al., 2000; Li et al., 2011). The annual rice straw generation amounts to 6,034,000 tons in Korea, which is the greatest among domestic agricultural by-products (KEC, 2013). Approximately 37.6% of the annually generated rice straw in Korea is recycled for animal feeding and other purposes, whereas the remaining 62.4% is treated as waste (KEC, 2013). Rice straw is a heterogeneous polymeric material composed of cellulose, hemicellulose, lignin, and other nonstructural carbohydrate components (Kaparaju et al., 2009; Li

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et al., 2011) that—if treated properly—can be converted into valuable resources such as methane, bioplastic, bioethanol, and protein (Abraham et al., 2016; Ahn et al., 2016; Huang et al., 2009; Lei et al., 2010; Mussoline et al., 2013; Sommart et al., 2000). The conversion of rice straw into useful resources can be an effective and sustainable alternative to treat the massive amount of the material that is currently disposed.

Anaerobic digestion has been widely used for valorization of organic wastes and their conversion into renewable energy such as methane gas (Chandra et al., 2012; Ge et al., 2016). Anaerobic digestion is known to have environmental and economic benefits such as energy recovery from its organic components and significant reduction of biomass (Lehtomäki and Björnsson, 2006; Nges et al., 2012). Organic matter in wastewater sludge, food waste, and high-strength wastewater is the typical substrate for anaerobic digestion, but use of lignocellulosic materials such as rice straw has recently gained interest as a means of producing renewable energy and to reducing greenhouse gas emissions (Mussoline et al., 2013; Sawatdeenarunat et al., 2015; Yan et al., 2015). Although challenges exist in the methanization of lignocellulosic materials because of their low conversion efficiency, the feasibility of this methanization can be improved by optimized digester design and operation, substrate pretreatment, or co-digestion with other organic wastes (Sawatdeenarunat et al., 2015).

Mixing intensity is one of the key operational variables that determine the performance of an anaerobic digestion process. Mechanical mixing homogenizes the contents of an anaerobic reactor and enhances the mass transfer of organic substrates to microbial biomass (Kaparaju et al., 2008). In addition, agitation helps to release trapped gas bubbles in the reactor, yielding uniformity of proper temperature and preventing sedimentation of denser particulate materials (Appels et al., 2008). A recent study demonstrated that the shear force generated by mechanical mixing is critical for formation and maturing of microbial granules via aggregation of flocculent biomass (Zhou et al., 2014). However, mixing has been shown to have not only positive but also negative impacts on the performance of anaerobic digestion. It was reported that overly intense mixing may lead to digester instability, reduced biogas production, and increased vulnerability to shock loadings (Kaparaju et al., 2008; Lindmark et al., 2014; Stroot et al., 2001). Therefore, it is important to provide an adequate intensity of mixing for a stable and efficient operation of an anaerobic digester. The optimal mixing intensity for anaerobic digestion should vary for different types of substrates and different modes of reactor operation (e.g., batch or continuous-flow) (Kaparaju et al., 2008; Lindmark et al., 2014; Li et al., 2015; Ong et al., 2002). The effect of mixing on anaerobic digestion has been mostly studied using relatively easily degradable substrates such as cattle manure and sewage sludge (e.g., Kaparaju et al., 2008; Ong et al., 2002; Stroot et al., 2001), and it is currently not well understood how mixing affects the anaerobic digestion of lignocellulosic biomass such as rice straw.

The objective of this study was to improve the understanding of the effect of mixing intensity on the performance of anaerobic digestion of rice straw. Laboratory-scale batch and semi-continuous reactors were used to investigate how the physical environment developed via different mixing conditions affects the interaction of microorganisms with the particulate substrate and how it relates to the hydrolysis of lignocellulosic materials in rice straw and, consequently, to the performance of anaerobic digestion.

2. Materials and methods

2.1. Preparation and analysis of substrate and inoculum

Rice straw was obtained from the Korea Rural Development Administration (Seoul, Korea). The rice straw was cut, ground with a mortar and pestle, passed through a sieve with 2 mm openings, and dried at 60 °C for 24 h prior to use as a substrate for anaerobic digestion. Digested sludge collected from the Jungnang Wastewater Treatment Plant located in Seoul, Korea was used as an inoculum. This inoculum was passed through a sieve with 0.5 mm openings and stored at 4 °C for a maximum duration of 48 h until use.

2.2. Batch reactors

Batch testing was conducted using a 600 mL serum bottle with 500 mL of inoculum and 5.76 g rice straw (5.0 g as volatile solids (VS)). The contents of the batch reactors were purged with nitrogen (> 99% purity) at the beginning of the test, and the bottle was sealed with a rubber stopper and an aluminum cap to maintain anaerobic condition. Seven different mixing conditions were applied: no mixing; once-a-week, twice-a-week, and once-a-day intermittent mixing; and 50, 150, and 300 rpm continuous mixing. For the intermittent mixing conditions, end-over-end mixing was applied manually 10 times per mixing event, otherwise the reactors remained undisturbed. Continuous mixing was applied using a horizontal shaker. The batch reactors were prepared in triplicate for all mixing conditions and were operated for 50 days at a temperature of 35 °C in a thermostatic room for mesophilic anaerobic digestion.

2.3. Semi-continuous reactors

Three semi-continuous reactors were operated at a working volume of 2.5 L and headspace of 1.5 L, with connections to allow continuous biogas ventilation and periodic substrate addition and effluent extraction. The substrate addition and effluent extraction were conducted on a daily basis, and the reactors were operated at a solid retention time (SRT) and hydraulic retention time (HRT) of 30 days throughout the operation. Identical operational conditions were applied for the three reactors during the initial period of 100 days for adaptation. A regime of 50 rpm continuous mixing was applied using a pitched-blade turbine-type impeller and the organic loading rate (OLR) was gradually increased from 0.1 to 1.0g VS/(L d) during the adaptation period.

After the adaptation period, different mixing regimes were applied for the three semi-continuous reactors. One reactor was operated with 50 rpm continuous mixing throughout the test. This reactor is referred to as “Reactor 1” henceforth. Intermittent mixing was applied in the second reactor. Once a day, the contents of the reactor were agitated 10 times via manual end-over-end mixing, otherwise the reactor was left undisturbed. The daily effluent extraction was conducted immediately after the manual mixing such that homogeneous mixed liquor could be extracted. This reactor is referred to as “Reactor 2” hereafter. The third reactor was operated at 50 rpm continuous mixing with occasional (i.e., two) high-speed (150 rpm) mixing events (henceforth referred to as “Reactor 3”). The high-speed mixing was applied for 19 days for the first event and 15 days for the second. Each of the three semi-continuous reactors was operated for a minimum of 300 days in a thermostatic room with a temperature of 35 °C. After the 100-day adaptation period, the OLR was maintained at 1.0g VS/(L·d) until the end of operation for all reactors.

2.4. Sampling and analysis

2.4.1. Biogas sampling and analysis

The biogas produced was sampled using 1-L Supel™ Inert Gas Sampling bags connected to each reactor, and its volume was recorded on a daily basis. The biogas contents (i.e., methane, nitrogen, and carbon dioxide) were analyzed using a gas chromatograph (GC; 6000 Series, ACME 6100, USA) using an 80/100 Porapak N column (Agilent Technologies, USA; 305 × 2.1 mm) and a thermal conductivity detector (TCD). Helium (> 99% purity) was used as the carrier gas. The oven was programmed as follows: 80 °C for 2.5 min, heated to 120 °C at 15 °C/min, and then held for 1.5 min.