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Enhanced methane production from rice straw co-digested with anaerobic sludge from pulp and paper mill treatment process

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HIGHLIGHTS

- An unique co-digestion strategy to improve degradation of rice straw was investigated.
- Different ratios of piggery wastewater and paper mill sludge were used as inocula.
- Specific methane yields above 330 LCH_4/kgVS were achieved in 92 days.
- Increased quantities of paper mill sludge directly increased hydrolysis of the straw.
- The most stable digester contained equal parts of straw, wastewater and sludge.

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ABSTRACT

Rice straw is a widely available lignocellulosic waste with potential for energy recovery through anaerobic digestion. Lignin slows the hydrolysis phase, resulting in low methane recovery and long digestion periods. Although pretreatment is effective, it often requires high energy inputs or chemicals that are not feasible for farm-scale systems. This study investigates a unique co-digestion strategy to improve methane yields and reduce digestion times for farm-scale systems.

By adding both piggery wastewater and paper mill sludge, specific methane yields in laboratory-scale digesters reached the theoretical value for rice straw (*i.e.* 330 L_NCH_4/kgVS) over the 92-day period. Accelerated hydrolysis of the straw was directly related to the quantity of sludge added. The most stable digester, with sufficient buffering capacity and nutrients, contained equal parts of straw, wastewater and sludge. This approach is feasible for farm-scale applications since it requires no additional energy inputs or changes to existing infrastructure for dry systems.

1. Introduction

Rice straw is an agricultural residue that is available in abundant supply, however, the uses for this material are limited mainly to cooking/heating fuel and animal feedstock (Contreras et al., 2012; He et al., 2008; Lianhua et al., 2010). Industrial uses are not fully realized and although some attempts are currently being made to capture the energy potential in large-scale applications (El-Hissewy, 2011; Li, 2011; Lim et al., 2012), most of the energy potential is lost through common practices such as open burning and tilling the straw back into the fields which both could contribute to methane gas emissions to the atmosphere (Contreras et al., 2012; Mussoline et al., 2013; Silvestre et al., 2013). Rice straw co-digested with animal manure in anaerobic conditions has been shown to be effective in both lab and pilot-scale experiments (Lianhua et al., 2010; Mussoline et al., 2012; Sun et al., 1987). Co-digestion improves substrate treatability since the straw material alone lacks alkalinity and appropriate nutrients to carry out the process (Mussoline et al., 2012). Although the energy recovery by means of anaerobic digestion is an attractive option, the primary obstacle of the process is the microbial degradation of the lignocellulosic material.

The anaerobic digestion of lignocellulosic material has been studied extensively in an attempt to overcome the challenge of degrading this tightly bound material and making it more available

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for energy conversion. The lignin content in agricultural residues, such as rice straw, makes degradation difficult because the lignocarbohydrate complexes create a barrier for microbial conversion (Ghosh and Bhattachatyya, 1999). Lignin is considered the most important factor affecting the hydrolysis of the cellulose component in the lignocellulosic material (Tong et al., 1990). Low methane yields and long digestion times are consistently observed with the anaerobic digestion of untreated rice straw, even when co-digested with animal manure (Dinuccio et al., 2010; El-Shinnawi et al., 1989; Mussoline et al., 2012). To date, delignification or some other type of pretreatment is used to separate the lignin from the cellulose so the cellulose can be fermented easily and converted to methane for energy recovery. Various studies have demonstrated the effectiveness of thermal, chemical and biological pre-treatment of the straw material (Ghosh and Bhattachatyya, 1999; He et al., 2008; Hendriks and Zeeman, 2009; Menardo et al., 2012; Zhang and Zhang, 1999; Zhao et al., 2010), however, these approaches are not typically energy efficient or practical in terms of design for farm-scale or industrial applications.

A different approach could be the integration of the appropriate microbes and/or enzymes necessary to break down the lignocellulosic material into the anaerobic digestion process via co-digestion. In fact, anaerobic sludge from a pulp and paper mill wastewater treatment facility, for example, may be an ideal candidate for co-digestion with rice straw since the biomass should be already adapted to lignocellulosic waste residues from the pulping process. By applying this approach, no separate pretreatment step that requires excessive chemicals, high temperatures for thermal pretreatment or aerobic conditions in the case of white-rot fungi is necessary. Although anaerobic reactors are commonly used in Europe for pre-treatment of high-strength wastewater generated by the pulp and paper industry for the combined benefit of COD removal and energy recovery (Habets et al., 2002), to the best knowledge of the authors, no application of pulp and paper waste and wastewater with other more refractory lignocellulosic materials are available.

The aim of this research is to study the effect of adding sludge collected from an anaerobic digester treating pulp and paper mill waste to rice straw in order to improve lignocellulosic material hydrolysis and thus methane production. Several anaerobic digesters were prepared using untreated rice straw as substrate and varying ratios of piggery wastewater and anaerobic paper mill sludge as inocula to determine optimum conditions for maximum methane yield. The experiments were performed in dry conditions. Advantages of dry digestion include less water input, higher loading rates, more stable digestion conditions, improved efficiency and potentially higher biogas yields (Lianhua et al., 2010; Lissens et al., 2001; Sun et al., 1987). The overall goal is to enhance the methane production by diversifying the microbial community and available nutrients using co-digestion with both agricultural and industrial residues rather than applying pretreatment strategies.

2. Methods

2.1. Experimental set-up

Biochemical methane potential (BMP) assays were conducted as described in previous studies (Angelidaki et al., 2009; Owens and Chynoweth, 1993). Known quantities of solid material and various fractions of different inocula were mixed thoroughly and added to 1-L glass bottles, flushed with N_2, sealed with metal screw caps and silicone septums, and placed in a thermostatically-controlled room maintained at 35 ± 2 °C. Temperature inside the room and atmospheric pressure conditions were recorded on a daily basis.

Methane gas was measured directly using a liquid-displacement method with 12% NaOH used as a barrier solution and converted to dry gas at 1 atm and 0 °C (STP). The digesters were connected to the inverted barrier solution via 21 gauge needles and tygon tubing (ID = 4.8 mm; OD = 8.0 mm). After the gas production rate stabilized (i.e. three days), the tubing was clamped and gas production was measured periodically for a total of 92 days.

2.2. Digester composition

Rice straw (i.e. substrate) was collected from a field in northern Italy in November 2011, approximately one week after the field was harvested, but prior to baling activities. The straw was sun-dried and stored in a cool, dry environment until the experiments were initiated in June 2012. Piggery wastewater was collected from a wastewater sump at a farm that raises fattening pigs in Zuid-Holland, the Netherlands. Anaerobic granular sludge was collected from a treatment facility in Eerbeek, the Netherlands, which treats a combined wastewater from five different pulp and paper mill plants. Both the wastewater and the sludge were stored at room temperature for less than a week and degassed before starting the experiment.

Rice straw was cut into 1-cm pieces and added as the substrate to eight experimental digesters (four digesters set up as duplicates) and two control digesters (C2, C3). Experimental digesters 1 through 4 (D1 to D4) contained differing fractions of pig wastewater and paper mill sludge. Control digester C2 contained rice straw mixed with autoclaved paper mill sludge and C3 contained rice straw only. The contents of the digesters (total weight ratios) are shown in Fig. 1. It was assumed that sufficient macro- and micronutrients would be supplied by the inocula mixture, thus no additional nutrients or buffers were supplied to the digesters. Both the experimental and control digesters were adjusted to 20% total solids (TS) by adding demineralized water, and thorough mixing was performed prior to establishing anaerobic conditions. Sludge blanks (D1b–D4b) were set up for each experimental digester, which contained the same quantity of inocula mixture, without substrate addition. In addition, a pressure-control bottle (C1) containing an equivalent amount of de-ionized water was initiated to account for the drip volume created by changing atmospheric conditions. The methane produced by the sludge blanks was subtracted to remove any contribution of gas from the degradable matter in the inocula. The specific methane yields were calculated by dividing the volume of methane produced at standard temperature and pressure (STP) by the weight of volatile solids (VS) of the rice straw added to each digester. The contents and quantities contained in the experimental digesters, control digesters, and sludge blanks are shown in Fig. 1.

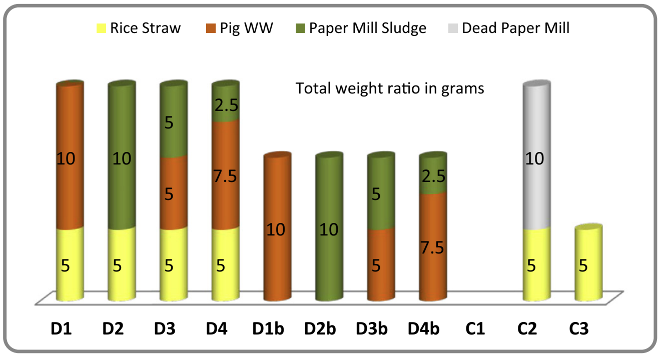

Fig. 1. Composition of experimental digesters, control digesters and sludge blanks.