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Research article

Importance of "weak-base" poplar wastes to process performance and methane yield in solid-state anaerobic digestion

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A B S T R A C T

Failure of methane yield is common for anaerobic digestion (AD) of "weak-acid/acid" wastes alone. In order to verify the importance of pH of materials on the process performance and the methane yield, the "weak-base" wastes-poplar wastes (PW) were used as substrate of solid-state AD (SS-AD). The results show that PW could be used for efficient methane yield after NaOH treatment, the total methane yield was 81.1 L/kg volatile solids (VS). PW also could be used for anaerobic co-digestion with high-pH cattle slurry (CM). For the group with NaOH pretreatment, time used for reaching stable state was 2 days earlier than that of the group without NaOH pretreatment. The maximal methane yield of 98.2 L/kg VS was obtained on conditions of 1:1 of PW-to-CM (P/C) ratio and NaOH pretreatment, which was 21.1% ($p < 0.05$) higher than that of PW. The maximal reductions of total solids (TS), VS, cellulose and hemicellulose were 51.3%, 57.5%, 46.0% and 47.0%, respectively, which were associated with the maximal methane yield. The results indicate that PW could be alone used for efficient SS-AD for methane yield after NaOH treatment.

1. Introduction

For continuous increase of greenhouse gas emission and severe depletion of fossil fuels, developing renewable energy becomes more and more imperative (Hamelinck et al., 2005; Sun et al., 2005). Based on the report of the Intergovernmental Panel on Climate Change (IPCC), United Nations, the worldwide energy supply will be substituted by renewable energy up to 77% by the year of 2050 (Edenhofer et al., 2011). Sustainable methane yield from biomass can effectively reduce the consumption of fossil fuels and the energy input of waste treatment industry, the yield of valuable organic fertilizers can be made simultaneously.

In recent years, solid-state anaerobic digestion (SS-AD) has been used for treating many types of bio-wastes for methane yield (De Baere et al., 2010; Li et al., 2011). The total solids content (TS%) of SS-AD can be up to 40% (Brown et al., 2012). SS-AD has many advantages over liquid-state AD (LS-AD), such as less requirements of energy and water resource, larger capacity of treating organic solids, and easier disposal of effluent due to low moisture (Aymerich et al., 2013; Di Maria et al., 2012; Martin et al., 2003). However, successful cases of SS-AD of agricultural wastes alone are few, because of the acidic phenomena and the resulted acidic inhibition on AD. Biogas yield from corn straw with NaOH pretreatment was feasible. However, it was conducted via LS-AD, heavy fluctuation of daily biogas yield appeared in the process of LS-AD (Zheng et al., 2009). Biogas yield from corn straw alone was investigated on conditions of NaOH pretreatment and 5% of TS, the results showed that the AD could proceed, but the process was not stable (Zhong et al., 2011).

Substrates used for methane yield are various. Lignocellulosic biomass has huge potential for methane yield, which mainly contains agricultural and forest wastes, such as corn straw, wheat straw, poplar wastes, willow wastes, and vegetable wastes.

Lignocellulosic wastes are usually used for methane yield; the related studies of the pH of AD are plentiful. It was mentioned that a pH between 7.0 and 7.2 was optimal for biogas yield, biogas yield was also satisfactory with pH in the range of 6.6–7.6, while biogas yield was negatively affected at a lower pH (<6) (Nagamani and Ramasamy, 1999). It was found that the neutral pH for AD was in the range of 6.9–7.57 (Bouallagui et al., 2009). Similar pH range of 6.6–7.8 was obtained on the optimal condition, the TS% was high (4–10%) (Yuan et al., 2011). Accurately, the operational pH of 7.4 was recommended (Lahav and Morgan, 2004). pH can be used for controlling the performance and the microbial community of AD.

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The ammonia content in biogas was effectively reduced from 332 ppm to 9 ppm by pH-based control (Strik et al., 2006). One investigation showed that pH within the growth optimum of microorganisms reduced the ammonia toxicity (Bhattacharya and Parkin, 1989). In a word, the previous studies were mainly focused on the pH of the reaction environment.

In addition to the pH of reaction environment, pH of materials is important for AD. pH values of wheat straw and corn straw are 6.3 and 6.4, respectively (Cui et al., 2011); pH values of fruit and vegetable wastes (VPWs) are 4.2–5.1 (Bouallagui et al., 2009; Molinuevo-Salces et al., 2012; Yao et al., 2014a). Low pH may contribute to the accumulation of acidic intermediates. This may be one of the reasons that some lignocellulosic wastes cannot be used for AD alone and should be used for anaerobic co-digestion with suitable materials, such as cattle manure (CM) and pig manure. Biogas yield from corn straw alone was studied, the daily biogas yield ceased due to the acidification. Although the daily biogas yield recovered later, fluctuations appeared during the process of AD (Chen et al., 2010). On the condition of 30% fruit and vegetable wastes/70% water, the lowest levels of daily biogas yield and methane yield were observed, and obvious fluctuation appeared during the process of AD (Bouallagui et al., 2009). Anaerobic co-digestion of VPWs with CM for methane yield was studied, when VPWs were used as the substrate of AD, failure of daily methane yield occurred at all inoculum proportions in mixtures, pH of the effluent was 5.6 (Yao et al., 2014a). The effect of pig manure-to-grass silage ratio on methane yield was evaluated, failure of daily methane yield occurred at 0:1 of pig manure-to-grass silage ratio, pH for grass silage was 4.5 (Xie et al., 2011). Therefore, these cases confirm that "weak-acidic/acidic" materials cannot be used for methane yield alone. However, previous studies of pH of materials were mainly focused on weak-acid/acid biowastes with low pH, few related studies have been done for "weak-base" biowastes with high pH.

Poplars are used for shelter forests against wind and fixing sand, commercial plantation, landscape engineering, and agricultural protection forest (Yao et al., 2013), so, a large amount of poplar wastes (PW) are produced from the wood process, such as sawdust, wood cuttings, and sapwood. The pH of PW is generally high and is about 7.0 (Yao et al., 2013), so PW can be called "weak-base" lignocellulosic materials. This characteristic may be helpful for improving the process performance of AD. This can be explained by the buffer capacity. Generally, high buffer capacity associated with high pH (Chaowana, 2013; Fengel and Wegener, 1984), so PW has higher buffer capacity than many biowastes like wheat straw and VPWs as aforementioned. Accordingly, lignocellulosic materials with high buffer capacity are "weak-base" like rice straw (Kwon et al., 2013). PW are mainly composed of cellulose, hemicellulose, and lignin. The complex structure of native lignocellulose creates recalcitrance to enzymatic hydrolysis (Zhu et al., 2010). Therefore, pretreatment is necessary to improve the biodegradability of PW in order to improve the methane yield (Ariunbaatar et al., 2014; Harris and McCabe, 2015). As one of the leading pretreatments, alkaline pretreatment has several advantages, such as solubilization of lignin, neutralization of various acidic products, and prevention of pH drop during the acidogenesis process of AD (Hendriks and Zeeman, 2009; Pavlostathis and Gossett, 1985). Sodium hydroxide (NaOH) is one of the most effective alkaline reagents for removing lignin and improving biogas yield. Acidic intermediates produced during pretreatment can be neutralized by NaOH to some extent, which is beneficial for the subsequent process stability of AD (Hendriks and Zeeman, 2009; Pavlostathis and Gossett, 1985). In addition, cation (Na^+) released from NaOH contributes to the increase of electrical conductivity in digester, which can enhance methanogenesis via CO_2 reduction by enhancing extracellular electron transfer (Qiao et al., 2015). As is known, the ability of mass transportation in SS-AD is lower than LS-AD (Li et al., 2011), so Na^+ can help enhancing the electrical conductivity, and then the improvement of methane yield (Qiao et al., 2015).

Based on the failure cases of SS-AD with "weak-acid" biowastes as substrate for methane yield, SS-AD of "weak-base"-PW alone with NaOH pretreatment was raised in present study in order to validate the importance of pH of materials on SS-AD. Because of the high buffer capacity of PW as aforementioned, the stable process and the improvement of methane yield are anticipated. In addition, anaerobic co-digestion of PW with CM for methane yield may be an ideal approach to treat these two types of biowastes, which not only reducing the cost, but also providing balance nutrients for the enhancement of the process stability of AD and the improvement of the methane yield. The pH of CM is high (pH = 8.3) (Yao et al., 2014a, 2014b), which is usually adopted for co-digestion with the lignocellulosic wastes. However, PW and CM are all "weak-base" materials, studies on SS -AD of "weak-base" materials and CM are few. Therefore, if SS-AD of CM and PW is feasible, there will be one more approaches to utilize this forest wastes for energy recovery. The present study also can be a reference for utilizing other types of "weak-base" biowastes for methane yield.

Based on the above, the purpose of this study were: (1) to verify the anticipation that the "weak-base"-PW is beneficial for the enhancement of process stability of SS-AD; (2) to determine whether the "weak-base"-PW can be used for co-digestion with high pH-valued CM; (3) to evaluate the process performance of SS-AD, such as start-up, process stability, and methane yield.

2. Materials and methods

2.1. Feedstock and inoculum

PW were collected from a wood processing factory located in the suburb of Jiuquan City, Gansu Province, China. The PW were cut and grounded into 6–12 mm particles by a hammer mill (RT-34, Beijing Wei Bo Chuang, China). The resultant samples were stored at −20 °C prior to use. CM and inoculum were collected from a biogas plant digesting manure in Linxia, Gansu Province, China. The characteristics of PW, CM and inoculum are shown in Table 1.

2.2. Pretreatment

According to previous study, PW were pretreated with 3.0% NaOH (weight/weight) based on dry matter (Yao et al., 2013). The moisture contents was 88% (Zheng et al., 2009). Treatment with no NaOH was conducted. All the prepared samples were kept at ambient temperature (20 ± 1 °C) for 4 days.

Table 1
Characteristics of poplar wastes, inoculum and cattle slurry.

Parameter	Poplar wastes	Inoculum	Cattle slurry
Total solid (%)	83.6 ± 0.0	7.2 ± 0.1	25.6 ± 0.0
Volatile solid (%) (% of TS)	89.8 ± 0.3	58.3 ± 0.2	72.6 ± 0.0
Total carbon (%)	45.9 ± 0.1	29.8 ± 0.1	36.4 ± 0.0
Total nitrogen (%)	0.2 ± 0.0	1.9 ± 0.1	1.8 ± 0.1
H (%)	5.6 ± 0.2	4.0 ± 0.1	4.4 ± 0.1
pH value	7.3 ± 0.0	7.3 ± 0.0	8.3 ± 0.0
Cellulose (%)	55.3 ± 0.3	39.0 ± 0.8	31.4 ± 0.0
Hemicellulose (%)	26.1 ± 0.7	27.1 ± 0.7	28.3 ± 2.2
Lignin (%)	24.3 ± 1.4	ND	ND

ND: Not determined.