Energy Conversion and Management 112 (2016) 226–235

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Enhancement of biogas production in anaerobic co-digestion by ultrasonic pretreatment

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ARTICLE INFO

Article history:
Received 5 October 2015
Accepted 23 December 2015
Available online 23 January 2016

Keywords:
Biogas
Ultrasonic pretreatment
Anaerobic processes
SEM
Anaerobic co-digestion
Factor analysis

ABSTRACT

This paper optimized the anaerobic digestion (AD) pretreatment process and identified the influence of pretreatment on the co-digestion of maize straw (MS) and dairy manure (DM). In the study, ultrasonic was used to pretreat MS and DM prior to digestion, with power intensities of 0, 189.39, 284.09, and 378.79 kJ at 0, 20, 30, and 40 min, respectively. Changes in the surface structures of MS and DM were observed by scanning electron microscopy (SEM), and factor analysis was used to analyze the main factors affecting biogas production in the AD process. The result showed that the structure of DM was distributed and that the structure of MS became more roughness following the ultrasonic pretreatment (UP). The highest total biogas production of co-digestion (240.32 mL/g VS_{fed}) was obtained when MS was pretreated for 30 min without DM pretreatment ($MS_{30}DM_0$). This was significantly higher than that of the untreated sample (CK) (141.65 mL/g VS_{fed}). The cellulose activity (CA), reducing sugar (RS) content, volatile fatty acid (VFA) content and pH in the digester feed, and their maximum and minimum values in the AD process was affected by UP. Factor 1 of $MS_{30}DM_0$ was determined by RS content, pH and VFA content that they had the most influence on biogas production on days 6, 18, 24 and 30. Factor 2 of it was determined by CA, and it had most influence on days 0, 12, 36 and 42 in the AD process, The result of the factor analysis indicated that the main factors affecting biogas production were affected by UP and they differ according to the different digestion stages. This research concluded that UP improved total biogas production via changing the initial environment of AD and the environment during AD process, the changes made the environment more suitable for AD.

1. Introduction

Currently, due to increased energy security concerns, environmental impacts of the use of conventional fuels, improvements in the living standards and renewable technologies, the consumption of renewable energy is dramatically increasing [1]. However, as the amount of organic wastes generated from human, animal, and agricultural activities increases, environmental pollution problems are also growing rapidly [2]. Anaerobic digestion (AD) is a biochemical degradation process that is widely used for the treatment and energy recovery of many kinds of biomasses, especially agricultural products and agro-industrial wastes [3,4]. It is an efficient method for reducing wastes via the conversion of organic wastes into renewable energy, such as biogas for mitigating the energy crisis [5]. Unfortunately, due to the high carbon–nitrogen ratio (C/N) and the high content of lignin and hemicellulose contents in straw, biogas productivity is inhibited when straw is individually digested. This is mainly because a long time is required for bacterial regeneration with a low matrix metabolic rate and low offensive capability against toxic substances [6]. Additionally, there is a layer of wax on the epidermis of the straws, which limits the entry of water into the inner part of the straw, and thereby prevents the disintegration of cellulose. Furthermore, floating material and crusting phenomena also occur during the AD process, and decreases the methane permeability and the dischargeable capacity of the reactor [7]. Moreover, although anaerobic co-digestion (co-AD) of straw with manure could balance the C/N ratio and

Abbreviations: AD, anaerobic digestion; co-AD, anaerobic co-digestion; MS, maize straw; DM, dairy manure; SEM, scanning electron microscopy; UP, ultrasonic pretreatment; VS, volatile solid; CK, contrast sample; CA, cellulose activity; RS, reducing sugar; VFA, volatile fatty acid; TS, total solid; TNK, total Kjeldahl nitrogen; TOC, total organic carbon; C/N, carbon nitrogen ratio.

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http://dx.doi.org/10.1016/j.enconman.2015.12.087
0196-8904/

increase biogas production [8,9], it remains unclear whether the digestional efficiency is optimal. Hence, pretreatment could be an alternative which could improve biogas production by decreasing the contents of hemicellulose and lignin [10]. Different methods to pretreat straw have been introduced, and include physical methods, chemical methods, biological methods, and combined methods [11].

However, chemical pretreatment produces secondary pollution. Additionally, biological pretreatment conditions are difficult to control, and combined pretreatment usually has the disadvantages of both chemical and biological methods. In comparison, physical pretreatment methods are most commonly used due to operational convenience and low investment [12]. Ultrasonic pretreatment (UP) is a physical pretreatment, which enlarges the reaction boundary of the substrate that is created by degrading high polymeric matters and breaking the bonds at high temperature. Several studies suggest that ultrasonic can positively affect AD through the occurrence of acoustic cavitation phenomena [13]. These phenomena promote the physical disintegration of organic matter or the extraction of substances along with the enhancement of enzymatic activity [14–16]. Low frequencies (<100 kHz) promote mechanical and physical phenomena [17] and more efficient solubilization was achieved by the lowest frequency [18]. Various parameters including frequency, operation power, reaction time and temperature affect the ultrasonic process performance, reaction time and temperature [19]. Studies have showed that the floc size reduced from 94 μm to less than 3 μm with a sonication density of 0.22 W/mL and 0.44 W/mL, respectively [20], and the maximum power intensity was 88.6 kJ/kg [19]. After UP of livestock waste, 58% higher methane yield was achieved due to the decrease in the ammonia concentration (28%) and enhanced solubilization (51%) [21]. Compared to the untreated sample (CK), the biogas production of UP treated sample was increased by 90% [22]. Castrillón et al. [23] showed that co-AD of UP pretreated dairy manure and crude glycerin increased the methane production by 121%, compared with the co-AD of DM and crude glycerin [24].

However, limited information is available on the effect of UP on co-AD of MS and DM. Furthermore, the main factors of UP that influence the biogas production in AD are not clear. Very few studies have investigated the effects of UP on CA, RS content, pH and VFA content in the digester feed and AD process. Therefore, further investigation is required to clarify the role of UP in achieving efficiency of the co-AD performance. The aims of this paper included optimizing the AD pretreatment process, investigating the initial digestion performance after UP, and analyzing the correlation of CA, RS content, pH and VFA content during AD process, exploring the reason of UP to improve biogas production.

2. Materials and methods

2.1. Origin and characterization of substrates

In this study, MS and DM were collected from a livestock farm located in Yangling, China. The inoculum was obtained from household biogas digesters in a local biogas demonstration village in Yangling, China. The substrates and inoculum were individually homogenized and subsequently stored at 4 °C for further use. Table 1 shows the basic characteristic of fermentable substrates and inoculum. All samples were collected in triplicates, and the averages of the three measurements are presented.

Table 1
Basic characteristic of fermentable substrates and inoculum.

Material	Maize straw	Dairy manure	Inoculum
Total organic carbon (g/kg VS)	57.48 ± 0.3	65.12 ± 0.5	35.5 ± 0.3
Total nitrogen (g/kg VS)	1.68 ± 0.02	4.59 ± 0.03	1.69 ± 0.2
Carbon-to-nitrogen	34.17 ± 0.03	14.2 ± 0.2	21.01 ± 0.2
Total solid (%)	89.29 ± 0.7	22.2 ± 0.2	8.5 ± 0.09
Volatile solid (%)	94.97 ± 0.8	83.97 ± 0.7	70.2 ± 0.6

2.2. Experimental design

The MS and DM were pretreated by a KQ250B micro cleaning solution, with frequency and power of 50 kHz and 250 W, respectively. The water content of the micro cleaning solution was 60% and was obtained by immersing 1 kg of DM into a 2 L erlenmeyer flask. Following this, the erlenmeyer flask was placed into the micro cleaning solution. The DM was stirred every 10 min during the pretreatment. All samples were collected in triplicates, and the averages of the three measurements are presented. MS was added to pure water to reach the same water content as DM, and its pretreatment method was the same as that of the DM. The pretreatment times of MS and DM were 0, 20, 30 and 40 min. The power density (Es) was defined as the product of the ultrasonic power (*P*) and the ultrasonic time (*t*) divided by the sample volume (*V*) and the initial total solids concentration (TS_0) [25]. It is given by the following equation:

$$Es = \frac{(PT)}{(VTS_0)} \tag{1}$$

In this study, $P = 250$ W, $t = 0$, 20, 30 and 40 min (0 h, 1/3 h, 1/2 h, 2/3 h), $V = 1$ L, $TS_0 = 0.22$ kg. Es of each treatment was calculated and is presented in Table 2.

After the pretreatment, the MS and DM were mixed according to the ways shown in Table 3. The mass ratio of dry matter of MS to DM was 1:1, total dry matter was 56 g, MS and DM were 28 g and 28 g, respectively, volatile solid content (VS_{fed}) was 50.04 g (calculated according to Table 1), and inoculum was 200 g. Then, water was added to 700 g in a 1 L erlenmeyer flask [26]. AD was performed under mesospheric conditions ($T = 35 \pm 2$ °C) with a total solid concentration of 8% for 42 days. The displacement method was used to measure the biogas production in this study. Fig. 1 depicts the experimental equipment, which consisted of a 1 L erlenmeyer flask that functioned as the anaerobic digester (Fig. 1(7)) and served as the biogas collector (Fig. 1(13)) and a 1 L measuring cylinder (Fig. 1(14)) that was used to measure the water displaced from the collector. The digesters were placed at a constant temperature using a temperature controller. Biogas generated in Fig. 1(7) was transported into the headspace of the bottle using a glass pipe (Fig. 1(9)). The water in Fig. 1(13) was pressed out and overflowed into Fig. 1(14) through another glass pipe (Fig. 1(11)). The volume of the discharged water from the bottle represents the volume of the biogas generated in the digester. The experimental equipment used was similar to that described in Yin et al. [26]. Fig. 1 shows the experimental

Table 2
Power intensity and power density of ultrasonic pretreatment.

Treatments	MS power intensity (kJ)	DM power intensity *t* (kJ)	Total power intensity (kJ)	Power density (kJ/Kg $TS_0^{-1)}$
CK	0	0	0	0
MS_0DM_{20}	0	189.39	189.39	189.39(DM)
MS_0DM_{30}	0	284.09	284.09	284.09(DM)
MS_0DM_{40}	0	378.79	378.79	378.79(DM)
$MS_{20}DM_0$	189.39	0	189.39	189.39(MS)
$MS_{30}DM_0$	284.09	0	284.09	284.09(MS)
$MS_{40}DM_0$	378.79	0	378.79	378.79(MS)

Note: MS instead of maize straw and DM instead of dairy manure.