Bioresource Technology 146 (2013) 408–415

Contents lists available at ScienceDirect

Bioresource Technology

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

Anaerobic digestion of wheat straw – Performance of continuous solid-state digestion

Marcel Pohl *, Kathrin Heeg, Jan Mumme

Leibniz Institute for Agricultural Engineering Potsdam-Bornim e.V., Max-Eyth-Allee 100, 14469 Potsdam, Germany

HIGHLIGHTS

- Thermophilic anaerobic digestion of wheat straw was investigated (55 and 60 °C).
- Organic loading rate dependent behavior of the UASS system was analyzed.
- The influence of the substrate's chopping length on reactor performance was studied.
- Hydrolysis kinetics from steady state operation has been determined.
- Functional separation in the two-stage system for OLR $\geqslant 8\ g_{VS}\ L^{-1}\ d^{-1}$.

ARTICLE INFO

Article history:
Received 2 June 2013
Received in revised form 18 July 2013
Accepted 21 July 2013
Available online 27 July 2013

Keywords:
Anaerobic digestion
Solid-state
Methane
Wheat straw
Organic loading rate

ABSTRACT

In this study the upflow anaerobic solid-state (UASS) reactor was operated at various conditions to optimize the process parameters for anaerobically digesting wheat straw in a continuous process. Additionally, particle size effects have been studied in the operation at 55 and 60 °C. Moreover, the incremental effect of the organic loading rate (OLR) to the system was examined from 2.5 to 8 $g_{VS}\ L^{-1}\ d^{-1}$.

It was found that the UASS operating at 60 °C with a small OLR yields highest methane production, but the advantage over thermophilic operation is negligible. The rise in OLR reduces the systems yields, as expected. From OLR = 8 $g_{VS}\ L^{-1}\ d^{-1}$ a second stage is necessary to circumvent volatile fatty acids accumulation.

1. Introduction

Renewable energies play substantial role to fight against the global warming and climate change, as they are capable of delivering energy in a CO_2-neutral way. However, the production of photovoltaic and wind energy is strongly depending on meteorological conditions. Meanwhile, biomass delivers a steady energy output and the energy is therefore available for base-load power delivery. To circumvent the competition between energy and food production, the usage of waste materials for bioenergy production draws more attention. Wheat straw, for instance, is used for the production of bioethanol, biohydrogen and biogas. In a comparative study, the production of biogas from straw turned out to be the most energy efficient among those three (Kaparaju et al., 2009b) .

Straw consists of cellulose and hemicellulose, linked to the anaerobically non-digestible lignin. Therefore, anaerobic digestion of straw usually requires long retention times and thus, delivers comparably small methane yields with respect to time. Furthermore, straw addition increases the density of CSTR type reactors content and along the effort needed for mixing. To overcome these disadvantages of straw, a lot of effort is already placed into pretreatments for the improvement of bioavailability, even though it poses a major cost factor (Hendriks and Zeeman, 2009; Sapci, 2012; Nkemka and Murto, 2013). Straw's poor biodegradability was shown in its applicability as a suitable biofilm carrier in two-phase anaerobic digestion processes (Andersson and Björnsson, 2002; Svensson et al., 2007), as its decomposition by bacterial enzymes is comparatively slow. Another disadvantage of lignocellulosic substrates for anaerobic digestion is their poor nutrients content, which is necessary for microbial growth. This has to be compensated by co-fermentation (Nkemka and Murto, 2013) with a supplementing co-substrate, or by chemical additives (Kridelbaugh et al., 2013).

The UASS reactor, primarily presented by Mumme et al. (2010), was invented to provide high performance anaerobic digestion with little shear stress disturbing the biofilms developing in the solid-state bed and the anaerobic filter (AF), as it is known that

* Corresponding author. Tel.: +49 331 5699 921; fax: +49 331 5699 849.
E-mail address: mpohl@atb-potsdam.de (M. Pohl).

0960-8524/$ - see front matter
http://dx.doi.org/10.1016/j.biortech.2013.07.101

biofilm thickness decreases with the increase of shear stress (Paul et al., 2012). A two-stage system was used, as a spatial separation of hydrolysis and methanogenesis are known to improve AD performance. The UASS reactors, as well as the AF, were built without a stirrer, so the spatial vicinity of H_2-producing and -consuming microorganisms can be promoted, which is thermodynamically beneficial (Kim et al., 2002). Using maize silage as feedstock, the UASS reactor was able to operate at OLRs of up to 17 $g_{VS}\ L^{-1}\ d^{-1}$ with methane yields of 312 $L\ g_{VS}^{-1}$ (Mumme et al., 2010).

The most important process parameter of continuous anaerobic digestion operation is the organic loading rate (OLR). Increasing the OLR will proportionally reduce the solids retention time (SRT) as well as the methane building potential of the substrate. In terms of efficiency, the optimization of OLR and methane yield needs to be identified. Moreover, high biogas yields also have the advantage of leaving fewer residues for subsequent disposal and thus allow smaller reactor sizes, which is economically more attractive (Tong et al., 1990).

Previous experiments demonstrated the feasibility of the stable long-time anaerobic digestion of lignocellulosic substrate in the UASS system (Pohl et al., 2012). Those promising results encouraged to test the system for more operational parameters in order approach the optimal conditions. The emphasis of this study was to investigate the process behaviors and performances of the UASS system depending on the OLR with the aim to optimize process parameters. Additionally, as thermophilic anaerobic digestion in the UASS system showed higher methane yields than mesophilic fermentation (Pohl et al., 2012), an increase of temperature from 55 to 60 °C was tested for even further efficiency improvement. Moreover, the influence of the substrate's particle size on the UASS reactor was also studied.

2. Methods

2.1. Substrate characteristics

Wheat straw as a sole substrate was studied. After harvest, the straw was chopped on the field by a mobile chaff cutter (Ralle, Germany), afterwards milled in a straw mill (Himel, Germany) to its final average cutting length of 35 mm and removed from dust in a cyclone. Finally, the straw was pressed into bales. For comparative studies of the straw's chopping length, it was further chopped into halves using a hammer mill. In the following, this variety is denoted as "short".

The wheat straw used had a total solids (TS) content of 95.3%, 88.9% of volatile solids (VS) and a chemical oxygen demand (COD) of 1.19 $g\ g^{-1}$. Crude fiber content was determined to be 46.3% of the straw's dry matter. The substrate contained 15.8 $g\ kg^{-1}$ of total nitrogen and 0.07 $g\ kg^{-1}$ of ammonium. Volatile fatty acids (VFAs) in the substrate, calculated as the sum of concentrations of C2- to C6-acids, were at 2.06 $g\ kg^{-1}$. For thermophilic anaerobic digestion, the wheat straw showed a maximum methane yield of 304.29 $L\ kg_{VS}^{-1}$, which was determined according to the biochemical methane potential guideline VDI-Gesellschaft Energie und Umwelt (2006).

2.2. Reactor setup and operation

The technical setup consisted of four identical systems, each of them containing an UASS reactor and an AF to prevent VFA accumulation. The UASS reactors had a working volume of 39 L, leaving 10 L of headspace. The AFs of 30 L were filled with PE biofilm carriers ("Bioflow 40", RVT Process Equipment GmbH, Germany) with a surface of 305 $m^2\ m^{-3}$ for biofilm establishment. UASS reactors were built from stainless steel with an inspection window to control and measure the solid-state bed; AF reactors were built from transparent acrylic glass. The process liquid circulation was set to a flow rate of 2.6 $L\ h^{-1}$ using peristaltic pumps. The flowing regime for all reactors was from bottom to top. Both the UASS and AF reactors were heated by water jacked with LAUDA thermostats (Lauda, Lauda-Königshofen, Germany). To reduce heat loss, all process liquor lines and the AF reactors themselves were insulated. For inoculation, 3.5 kg of digestate from a previous experiment, digesting wheat straw as a sole substrate as well, were added to each UASS reactor. The inoculating digestate was characterized by a crude fiber content of 46.5%, volatile solids content of 107.7 $g_{VS}\ kg^{-1}$, and a pH of 9.1. The ammonium content was 0.56 $g\ kg_{FM}^{-1}$, the Kjeldahl-nitrogen content was determined to be 1.45 $g\ kg_{FM}^{-1}$. With four UASS–AF systems available, each experiment was run in duplicates to improve statistical certainty. A detailed description and a scheme of the technical setup can be found elsewhere (Pohl et al., 2012).

In contrast to prior experiments, where the stable long-time meso- and thermophilic operation at OLR = 2.5 $g_{VS}\ L^{-1}\ d^{-1}$ were shown (Pohl et al., 2012), several operational parameters have been modified for this study. The major alteration was the successive raise of the OLR throughout the experiment, which is following: 2.5, 3.5, 4.5, 6 and 8 $g_{VS}\ L^{-1}\ d^{-1}$ (equivalent to 3.1, 4.3, 5.6, 7.4 and 9.9 $g_{COD}\ L^{-1}\ d^{-1}$). The subsequent OLRs ran for at least twice of the SRT to ensure steady state in terms of performance parameters, mainly indicated by constant biogas production.

Earlier experiments also revealed that thermophilic anaerobic digestion of wheat straw at 55 °C in the UASS–AF system turned out to be more efficient than mesophilic operation (37 °C). Therefore, two of the four systems' UASS reactors were set to 60 °C for 76 days. For better differentiability, operations at 60 °C will be referred to as "hyperthermophilic" throughout this manuscript. The connected AFs were perpetually operated at 55 °C, which is known to be a favorable temperature for methanogenic microorganisms. Additionally, it was previously shown that temperature effects on the acceleration of hydrolysis, which is known to be the rate limiting step in anaerobic digestion. The hypothesis of this study was, that an increase in temperature from 55 to 60 °C could increase the efficiency by widening the bottleneck of hydrolysis in the UASS reactor, while keeping the methanogens in the attached AF at their preferred temperature. After the experiments with hyperthermophilic temperatures in the UASSs at OLR = 2.5 and 3.5 $g_{VS}\ L^{-1}\ d^{-1}$, those systems were set back to thermophilic temperature and fed with wheat straw of a shorter chopping length.

The reactors were fed once a day through a diagonal feeding tube to the bottom of the UASS reactor. Digestate removal was carried out once a week, but became necessary as much as twice for OLR $\geqslant$ 4.5 $g_{VS}\ L^{-1}\ d^{-1}$ for the thermophilic systems with the unchopped straw and for OLR = 8 $g_{VS}\ L^{-1}\ d^{-1}$ for the chopped-straw systems. The higher frequency turned out to be necessary to reduce the height of the solid-state bed, which would have blocked the diagonal feeding tube otherwise. Clogging by decomposed substrate was not observed. The volume taken out during digestate removal was compensated with water addition. Temperature measurements at different heights and radial positions inside the solid-state bed revealed differences below 1 K, so a homogenous temperature distribution was assumed.

Due to wheat straw's poor concentrations of trace elements, they had to be supplemented along with the feeding. Following the recommendation of Abdoun and Weiland (2009), medium No. 144 of the "Germany collection of microorganisms and cell cultures" (Brunswick, Germany) was added to the process liquor on a daily basis. The dosage was adjusted according to the organic loading rate. Among other trace elements, medium No. 144 contains iron, calcium, copper, zinc and sodium.