Bioresource Technology 129 (2013) 561–567

Contents lists available at SciVerse ScienceDirect

Bioresource Technology

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

Use of real time gas production data for more accurate comparison of continuous single-stage and two-stage fermentation

Jaime Massanet-Nicolau *, Richard Dinsdale, Alan Guwy, Gary Shipley

Sustainable Environment Research Centre, Faculty of Health, Sport and Science, University of Glamorgan, Pontypridd CF37 1DL, United Kingdom

HIGHLIGHTS

- Real-time measurement of biogas composition was used to determine biogas yields.
- An increase in methane yield of 37% was observed using two-stage fermentation.
- Two-stage fermentation could be performed at shorter HRTs and higher OLRs.
- Methane yields from two-stage were greater than those predicted by a BMP test.
- Two-stage fermentation also produces hydrogen, resulting in greater energy yields.

ARTICLE INFO

Article history:
Received 4 September 2012
Received in revised form 19 November 2012
Accepted 22 November 2012
Available online 5 December 2012

Keywords:
Anaerobic
Digestion
Two-stage
Methane
Hydrogen
Yield

ABSTRACT

Changes in fermenter gas composition within a given 24 h period can cause severe bias in calculations of biogas or energy yields based on just one or two measurements of gas composition per day, as is common in other studies of two-stage fermentation. To overcome this bias, real time recording of gas composition and production were used to undertake a detailed and controlled comparison of single-stage and two-stage fermentation using a real world substrate (wheat feed pellets). When a two-stage fermentation system was used, methane yields increased from 261 L kg^{-1} VS using a 20 day HRT, single-stage fermentation, to 359 L kg^{-1} VS using a two-stage fermentation with the same overall retention time – an increase of 37%. Additionally a hydrogen yield of 7 L kg^{-1} VS was obtained when two-stage fermentation was used. The two-stage system could also be operated at a shorter, 12 day HRT and still produce higher methane yields (306 L kg^{-1} VS). Both two-stage fermentation systems evaluated exhibited methane yields in excess of that predicted by a biological methane potential test (BMP) performed using the same feedstock (260 L kg^{-1} VS).

1. Introduction

The increasing cost of fossil fuels, combined with concerns about their impact on our environment has led to a renewed interest in biomass as a sustainable, alternative energy (Patterson et al., 2008, 2011; Murphy and Power, 2009). Biomass can be used to produce both hydrogen and methane via anaerobic fermentation (Guwy et al., 2011). The biomass may be specifically produced for bio-energy production (such as an energy crop); or it may be a waste product from an industrial or municipal source. Most full scale anaerobic fermentation systems are of a single-stage design and produce methane (De Baere, 2006). There are however, many variations on this standard configuration, one of which is two-stage fermentation, where an additional, acidogenic fermentation stage is used to convert the biomass to organic acids which may then be used as substrate for the methanogenic fermenter (Khalid et al., 2011).

The use of two-stage, anaerobic fermentation to produce energy from biomass has been the subject of previous research spanning many years (Ghosh, 1991; De Gioannis et al., 2008). Two-stage processes have also been deployed to treat structurally complex biomass at full scale (Lee and Chung, 2010). In most cases a range of potential benefits have been put forward including greater process stability, and increased methane yields. Two-stage fermentation systems are also ideally suited to performing fermentative hydrogen production, since this results in high concentrations of volatile fatty acids which are an ideal substrate for methanogenic fermentation (Kyazze et al., 2008; Massanet-Nicolau et al., 2010).

Despite the proposed benefits of two-stage fermentation and the large body of literature pertaining to it, there are comparatively few studies where a direct comparison is made between single and

* Corresponding author.
E-mail address: jmassane@glam.ac.uk (J. Massanet-Nicolau).

0960-8524/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.biortech.2012.11.102

two-stage fermentation using lignocellulosic biomass sources. Where such studies are reported, their experimental design often makes it difficult to directly quantify the benefits resulting from two-stage fermentation. In several instances, researchers have conducted two-stage fermentation experiments and compared their yields with those published by other groups, who have performed single-stage fermentation using a similar substrate (Demirel and Yenigün, 2002; Chu et al., 2008). There are problems with this approach since apparatus, methodology and substrates can all vary between research groups. Relatively few researchers report on controlled comparisons between single-stage and two-stage fermentations such as that by Nielsen et al. (2004) which used cow manure as a substrate. Many groups also measure biogas composition once or twice per day due to economic and technological constraints (Nielsen et al., 2004; De Gioannis et al., 2008; Luo et al., 2011). However, the methane content of the biogas can vary considerably during a 24 h period, particularly if the fermenter is fed only once during this time, as is common in laboratory conditions. As a result calculations based on this methodology would severely over or under estimate methane production, depending on where in the daily cycle methane content is measured.

The lack of controlled and accurate data pertaining to two-stage fermentation of lignocellulosic biomass has meant that its potential benefits are not well perceived within industry. Often strategies to increase methane yield are pursued, which are costly and energy intensive and may not be any more effective than two-stage fermentation. Studies which accurately and definitively quantify the benefits of two-stage fermentation from lignocellulosic biomass are therefore of great value. Ideally, such studies should utilize lignocellulosic biomass that exists in sufficient quantities to be exploited for bio-energy production; they should involve single-stage and two-stage experiments conducted in parallel, using exactly the same feedstock and should include detailed recording of key parameters such as gas production and composition.

The feedstock used in this study is pelleted wheat feed, a co-product from the flour milling industry. Wheat feed is sold as animal feed, but the price it commands for this purpose is volatile and so there is increasing interest in using this kind of material as a biomass source for energy production (Hussy et al., 2003). The material contains the bran and endosperm of the wheat and so contains a high amount of complex carbohydrates such as cellulose and hemicellulose. The annual world wide production of this material is estimated at over 96 million tonnes (Hawkes et al., 2007a), making it a realistic source of biomass for bio-energy production.

The work presented here is a direct comparison of single-stage and two-stage fermentation of wheat feed pellets. The study is designed to adhere to the criteria listed above, and evaluates the effect of performing two-stage fermentation on biogas and energy yields, process stability, and effluent characteristics.

2. Methods

Three different fermentation systems were evaluated. The first of these was a conventional, single-stage fermenter with a hydraulic retention time (HRT) of 20 days, a configuration similar to that of a digester at a sewage treatment works and other scenarios where low grade biomass is treated via anaerobic fermentation (Tchobanoglous et al., 2002; Bolzonella et al., 2005). This was compared with two, two-stage fermentation systems, one having an overall HRT of 20 days and a second with a HRT of 12 days overall. To perform an accurate comparison, the fermentation systems were operated simultaneously using the same feedstock. Fig. 1 is a schematic showing the design of the fermentation systems.

The substrate used during these experiments was wheat feed pellets obtained from a flour mill operating in South Wales. The

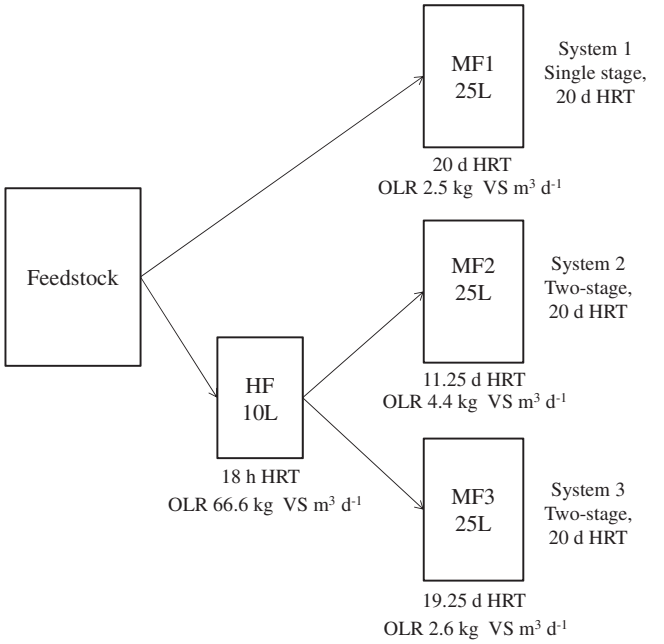

Fig. 1. Schematic showing arrangement of single and two-stage fermentation experiments. HF–hydrogen fermenter, MF–methane fermenter.

pellets contain high levels of structurally complex carbohydrates (up to 65% holocellulose (Hawkes et al., 2007a,b)), so to improve fermentation they were partially hydrolysed using alkali, before being fed into the fermenters. The pellets were soaked in water overnight in a refrigerator allowing them to break apart. They were then diluted with water and sufficient NaOH to raise the pH to 12 and to obtain a volatile solids (VS) content of 50 g L^{-1}. This feed was then transferred to a feed storage tank where it was pumped into the fermenter as required. The storage tank was maintained at a temperature of 2–8 °C to limit microbial growth. The high pH resulting from the alkali pre-treatment also helped to limit microbial activity during storage.

The inoculum used in these experiments was anaerobic digester effluent taken from a local sewage treatment works. Prior to use in the hydrogen fermenter, the inoculum was heated to 110 °C for 20 min to inactivate methanogenic microorganisms. In the methanogenic fermenters the inoculum was used without modification.

A continuously stirred hydrogen fermenter with a working volume of 10 L was used in these experiments. The hydrogen fermenter was equipped with instrumentation allowing pH, redox potential, and temperature to be continuously monitored during fermentation. The hydrogen fermenter was equipped with sensors for continuous measurement of both gas production and composition (H_2, CO_2 and CH_4). These variables were recorded using a PC equipped with a data acquisition card and a custom monitoring program written using the LabView™ programming package. The contents of the hydrogen fermenter were maintained at 35 °C using a thermostatically controlled electric heating jacket. The pH of the fermenter was maintained above 5.5 via the automated addition of 2 M NaOH. The fermenter was fed automatically, via computer controlled valves once per hour with sufficient feedstock to maintain a HRT of 18 h.

Fermentation was started by filling the fermenter with 5% inoculum and 95% feedstock by volume. In order to build up levels of hydrogen producing microorganisms, the fermenter was initially operated in batch mode until production of hydrogen occurred (approximately 18 h). Continuous feeding then commenced and the fermenter was operated for a period of 60 days prior to the commencement of this study, to allow a steady state to be reached.