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Utilising biohydrogen to increase methane production, energy yields and process efficiency via two stage anaerobic digestion of grass

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HIGHLIGHTS

- Continuous, two stage anaerobic digestion of grass was performed successfully.
- Two stage AD was compared with single stage AD in parallel.
- 13% more energy was obtained from comparable substrate utilisation with two stage.
- Two stage AD increased process stability and required shorter retention times.

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ABSTRACT

Real time measurement of gas production and composition were used to examine the benefits of two stage anaerobic digestion (AD) over a single stage AD, using pelletized grass as a feedstock. Controlled, parallel digestion experiments were performed in order to directly compare a two stage digestion system producing hydrogen and methane, with a single stage system producing just methane. The results indicated that as well as producing additional energy in the form of hydrogen, two stage digestion also resulted in significant increases to methane production, overall energy yields, and digester stability (as indicated by bicarbonate alkalinity and volatile fatty acid removal). Two stage AD resulted in an increase in energy yields from 10.36 MJ kg^{-1} VS to 11.74 MJ kg^{-1} VS, an increase of 13.4%. Using a two stage system also permitted a much shorter hydraulic retention time of 12 days whilst maintaining process stability.

1. Introduction

Increasing global energy consumption combined with concerns about the environmental damage caused by continued dependence on fossil fuels has prompted a great deal of research into alternative sources of energy which are both sustainable and carbon neutral. One such energy source is biomass which can be converted into energy rich gases such as hydrogen and methane via anaerobic digestion (AD). A large range of biomass types are compatible with anaerobic digestion, including municipal and industrial waste streams as well as crops grown specifically for energy production. One such energy crop is grass, which can be grown on marginal land not used for the production of food (Tilman et al., 2006). Such grassland accounts for 30% of the UKs land use and includes agricultural land which has been set aside under EU agricultural policies. Grasses are typically high in sugars such as fructose and lower in lignocellulose than many other bioenergy crops and so are ideally suited to fermentative energy production (Adler et al., 2006; Allison et al., 2009). Maintaining grass lands confers other environmental benefits such as sequestering carbon in the soil (Murphy and Power, 2009). Additionally, if the reduction in sheep and cattle farming in the UK over the last decade continues, a surplus of grass will be available for bioenergy production (CROPGEN, 2007). Mathematical models developed at Aberystwyth University indicate that if 25% of the UK's permanent grassland were used, 12,945 million tonnes of grass of grass per annum could be produced (Toop, 2013). Even at currently reported hydrogen and methane yields this would represent a significant source of sustainable, carbon neutral bioenergy.

Anaerobic digestion as a means of producing bioenergy is a well-established process worldwide; however innovations are constantly being made, enabling the process to cope with a wider range of feedstocks, to produce higher yields of energy, and to operate at lower costs and greater efficiency. One such innovation is two stage digestion in which the feedstock is digested in two

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separate stages, a high rate acidogenic stage and a slower methanogenic stage. Many advantages have been claimed for two stage anaerobic digestion, including greater process stability and higher yields (De Gioannis et al., 2008; Lee and Chung, 2010). Two stage AD can also be used to produce hydrogen during the acidogenic stage in addition to methane (Guwy et al., 2011).

Two stage AD has been studied at various scales using a range of feedstocks (Dareioti and Kornaros, 2014; Zuo et al., 2014), however there are comparatively few robustly controlled studies where it is compared with single stage AD using complex feedstocks. In many cases researchers conduct two stage AD trials and compare their results with those obtained by other groups using single stage AD (Chu et al., 2008). This approach is problematic since there is little consistency with regards to feedstock, methodology or process performance measurement. The operation of two stage AD experiments in the laboratory are also limited by the capability of lab scale digestion apparatus. In particular due to the problematic rheology of feedstocks with a high solids content, digesters must be fed manually, usually only once or twice per day, the same is true of gas production and composition measurements. Methane and hydrogen production can vary greatly in response to feeding events, consequently depending on when digesters are fed and when gas production is measured, yields of methane or hydrogen can be severely under or over estimated.

The lack of detailed, controlled and robust evaluations of two stage AD using complex feedstocks has meant that its advantages are not well understood within the industrial sector. This often leads to more costly and energy intensive methods being used to improve methane yields such as thermal hydrolysis. Despite this, some well designed and controlled studies have clearly demonstrated the benefits arising from two stage AD. Nielsen et al. (2004) demonstrated improvements in performance using two stage AD to treat cow manure, and recently the University of South Wales demonstrated a 38% increase in energy yields using two stage AD with flour milling co-product (Massanet-Nicolau et al., 2013).

The research reported here is a comparison of two stage and single stage digestion systems using pelletized grass as a feedstock. The study is designed to address the shortcomings of previous evaluations of two stage digestion discussed above; two stage and single stage digester systems are evaluated simultaneously using exactly the same batches of feedstock and gas production rates and composition are measured in real time to avoid bias when calculating methane and hydrogen yields. The study quantifies the advantages of two stage hydrogen/methane digestion in terms of overall energy yield, process stability and process efficiency.

2. Methods

2.1. Digestion experiments

Three different digester systems were evaluated in parallel, each using the same feedstock. The first of these was a single stage digester with a relatively long hydraulic retention time (HRT) of 20 days, producing just methane. This configuration is similar to conventional AD methodology employed at sewage treatment works. Secondly, a two stage system was evaluated, comprising a hydrogen producing digester with an 18 h HRT and a methane producing digester with a HRT of 11.25 days for an overall HRT of 12 days. Finally another two stage system was evaluated, again with a hydrogen stage of 18 h HRT, but with a methane stage of 19.25 days so that the overall HRT was 20 days, equal to the single stage system being evaluated. Fig. 1 is a schematic showing how these digestion systems were evaluated in parallel.

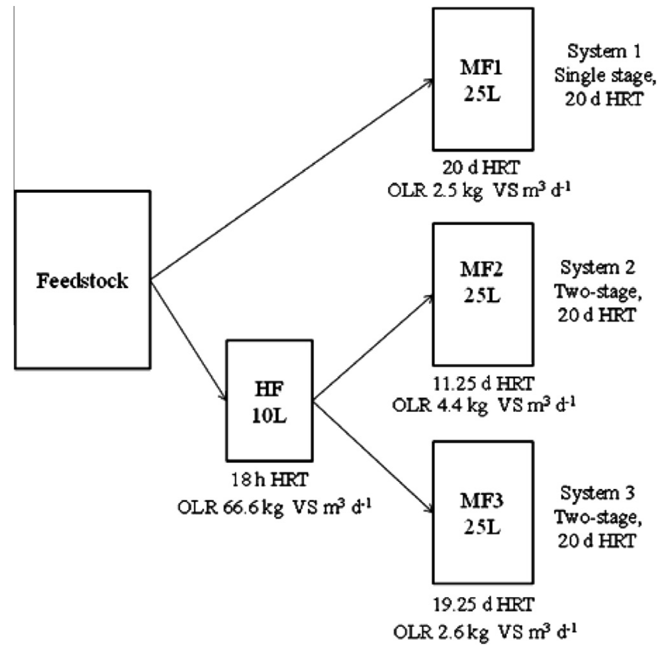

Fig. 1. Experimental design of parallel single and two stage digestion experiments.

2.2. Hydrogen digester

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

The hydrogen producing digester was started by filling it with 5% heat treated inoculum and 95% feedstock by volume. In order to build up levels of hydrogen producing microorganisms, the digester was initially operated in batch mode (with no additional feeding) until production of hydrogen occurred (approximately 18 h). Continuous feeding then commenced and the digester was operated for a period of 30 days prior to the commencement of this study in order to allow hydrogen production to stabilize as indicated by the stability of key parameters including biogas production and composition, pH and VFA production.

2.3. Methane digesters

Three identical methane digesters with working volumes of 25 L were used in these experiments. As with the hydrogen digester, these were equipped with sensors enabling continuous measurement and recording of gas production as well as CO_2 and CH_4 content. The contents of the digester were maintained at 35 °C using a thermostatically controlled water bath. The pH of the digesters was not actively controlled but was monitored daily to ensure it remained at pH 7.0 ± 0.5. The digesters were fed