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Improving biogas quality and methane yield via co-digestion of agricultural and urban biomass wastes

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ABSTRACT

Impact of co-digestion versus mono-digestion on biogas and CH_4 yield for a set of five biomass materials (vegetable food waste, cow dung, pig manure, grass clippings, and chicken manure) was investigated considering 95 different biomass mixes of the five materials under thermophilic conditions in bench-scale batch experiments over a period of 65 days. Average biogas and CH_4 yields were significantly higher during co-digestion than during mono-digestion of the same materials. This improvement was most significant for co-digestion experiments involving three biomass types, although it was independent of the specific biomasses being co-digested. Improvement in CH_4 production was further more prominent early in the digestion process during co-digestion compared to mono-digestion. Co-digestion also appeared to increase the ultimate CH_4/CO_2 ratio of the gas produced compared to mono-digestion although this tendency was relatively weak and not statistically significant.

1. Introduction

As a result of the increasing global energy demand and the negative environmental effects associated with energy production based on fossil fuels, such as global warming and air pollution, the interest in alternative, cleaner and more sustainable energy sources, such as biomass, is growing rapidly. Although biomass can only supply part of the current global energy needs it is an important energy source and will likely have a key role in the transition of the world's energy supply from fossil fuel based energy to sustainable energy production (Adelard and Poulsen, 2015; Mao et al., 2015). In this context biomass wastes from agriculture (animal manure) and urban areas (food waste, yard and park waste) constitute key sources of secondary biomass materials, suitable for energy production (Hoogwijk et al., 2003; Koch et al., 2015; Wirsenius, 2000).

Because biomass materials generally contains high amounts of water (50–98% by weight), energy extraction using thermal treatment methods, such as incineration or thermal gasification is less optimal because evaporation consumes a large fraction of the energy released. This problem is avoided when using anaerobic digestion and digestion is therefore often preferred when extracting energy from wet and easily degradable biomass materials (Li et al., 2015; Yong et al., 2015; Zarkadas et al., 2015). Furthermore, anaerobic digestion has the advantage that the nutrients (primarily N and P) in the biomasses are preserved and may be recycled together with remaining organic matter in the digested biomass, for use as fertilizer and soil amendment in agricultural production (Frigon and Guiot, 2010; Mao et al., 2015; Pagés-Díaz et al., 2011).

Anaerobic digestion of waste materials may be carried out on single materials (mono-digestion) or on mixes of multiple materials (co-digestion). Mono-digestion is often used for digesting animal manure at the individual farm level in relatively small anaerobic digestion plants while co-digestion is typically used in larger plants treating biomass wastes from multiple sources (farms, residential areas and industry). While thermal, chemical or thermo-chemical pre-treatment of biomass prior to digestion can improve CH_4 yield (Rafique et al., 2010; Rodríguez-Abalde et al., 2011; Valo et al., 2004), several recent studies have shown that co-digestion alone (without pre-treatment), can improve specific biogas and CH_4 yield compared to mono-digestion. Most existing studies have been based on biomass mixtures using either sewage sludge or a variety of animal manures together with materials such as food waste, energy crops or crop residues. Examples of key studies on co-digestion are: Kim et al. (2003), Koch et al. (2015), and Murto et al. (2004), who used sewage sludge mixed with residential or industrial food waste. In other studies Adelard and Poulsen (2015), Ashekuzzaman and Poulsen (2011), Lansing

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et al. (2010a, 2010b), Li et al. (2015), Magbanua et al. (2001), Wang et al. (2012, 2013), Yong et al. (2015), and Zarkadas et al. (2015), used mixtures of animal manure such as cow dung, pig manure or poultry manure in combination with food waste or crop residues (straw). A number of researchers further investigated co-digestion of industrial wastes such as cheese whey, food waste, and slaughter house wastes in combination with municipal solid waste and animal manure (Agdag and Sponza, 2007; Gelegenis et al., 2007; Ogejo and Li, 2010; Pagés-Díaz et al., 2011, 2014, 2015; Rico et al., 2015). Co-digestion of energy crops (grass, maize, algae biomass) with animal manure or sewage sludge was investigated by Ahn et al. (2010), Amon et al. (2007), Kim and Kang (2015), and Zaki-ul-Zaman et al. (2011). Co-digestion of biomasses (municipal solid waste, fruit waste or vegetable waste) not involving sewage sludge or animal manure was investigated by Anjum et al. (2012), Lin et al. (2011), and Ponsa et al. (2011). More comprehensive reviews of recent advances in anaerobic co-digestion are presented in Mao et al. (2015) and Mata-Alvarez et al. (2014). The majority of existing studies on biogas and CH_4 yield during co-digestion including almost all of the studies listed above, show that co-digestion results in improved production compared to what would be expected based on results from mono-digestion of the same materials. Thus, co-digestion appears to have a synergetic effect on both biogas and CH_4 production.

Although several studies including Pagés-Díaz et al. (2011, 2014, 2015) and Wang et al. (2012, 2013), have measured biogas and CH_4 potentials during both mono- and co-digestion as a function of biomass mix composition, only relatively few studies have investigated and assessed the impact of biomass mix composition on the synergetic or antagonistic effects of co-digestion on biogas and CH_4 potential. In addition Koch et al. (2015) and Wang et al. (2012, 2013) further showed that although co-digestion generally has a positive synergetic effect on biogas and CH_4 yield compared to mono-digestion, this is not always the case and the effect is often strongly dependent on the composition of the biomass mix being co-digested. There is thus a need to provide a more thorough statistical assessment of the probability of synergy during anaerobic digestion.

The majority of studies on biogas and CH_4 production during anaerobic co-digestion have been carried out using biomass mixes consisting of only two different biomass materials (Mao et al., 2015; Mata-Alvarez et al., 2014) while a smaller number of studies including Giuliano et al. (2013), Kim and Kang (2015), and Wang et al. (2012, 2013) have considered mixes consisting of three materials. The authors are only aware of two studies considering mixes containing four biomass materials (Pagés-Díaz et al., 2011, 2014) and are not aware of any studies considering co-digestion of mixes containing 5 or more biomass materials. As most large-scale co-digestion plants often digest materials from several different sources, additional studies of co-digestion with mixes consisting of three or more biomass materials are needed to gain understanding of the potential for improving biogas and CH_4 potential via co-digestion of multiple biomass materials.

Most studies on the effects of biomass mix composition on the performance of anaerobic co-digestion in comparison with mono-digestion, have typically considered less than 10 different biomass mix compositions for the same set of biomasses, however a smaller number has considered 10–15 mix compositions These include Pagés-Díaz et al. (2014), Wang et al. (2013), and Yong et al. (2015). The authors have not been able to identify any studies considering >15 mix compositions for the same set of biomasses. As pointed out above, synergetic effects of co-digestion on biogas or CH_4 potential can vary strongly with biomass mix composition. A larger number of biomass mix compositions for a given set of biomasses should therefore be used when assessing the probability that co-digestion will improve biogas and CH_4 yield for a given set of biomasses. This is especially the case when three or more biomasses are co-digested. There is therefore a need for further co-digestion experiments based on a larger number of biomass mixes than considered previously.

The objective of this study was therefore, to investigate the impact of co-digestion on biogas and CH_4 yield for a set of five waste biomasses (vegetable food waste, yard/park waste, cow dung, pig manure, and chicken manure) as compared to mono-digestion. These materials were chosen to represent urban (food waste and yard/park waste) and agricultural wastes (cow dung, pig manure and chicken manure) commonly available for digestion in highly populated and intensively farmed regions such as Northwest Europe, parts of Southeast Asia and North America. Synergetic effects on both CH_4/CO_2 ratio and CH_4 yield as a result of co-digestion in comparison with mono-digestion were assessed. This was done both with respect to the ultimate values of CH_4/CO_2 ratio and CH_4 potential, as a function of the composition of biomass mix, and as a function of digestion time.

2. Materials and methods

2.1. Substrates and inoculum

Five different biomass materials; cow dung (CD), chicken manure (CM), vegetable food waste (FW), grass clippings (GC), and, pig manure (PM) were used. Food waste and grass clippings were collected in a residential area in Aalborg, Denmark while cow dung, pig manure and chicken manure were collected at local farms near Aalborg, Denmark. All materials were stored at 4 °C until use. Inoculum was digestate collected at a full-scale digester located at the Faculty of Agricultural Science, Aarhus University, Foulum, Denmark. This digester was treating a mixture of agricultural wastes (pig manure, fur animal droppings and straw) at the time of collection. This inoculum was chosen as it was well adapted to the types of biomasses considered in this study and any lag effects should therefore be at a minimum. The inoculum was collected about a week before it was needed and starved prior to use to reduce its gas production during the experiments. A relatively large number of co-digestion experiments (95) were considered in this study. In order to manage gas sampling in a satisfactory manner, these experiments were carried out in smaller sets (of 30–60 individual samples) over a period of about 9 months. As a result of this it was necessary to collect fresh biomass materials and inoculum multiple times during this period. All biomasses with the exception of PM which was on liquid form were initially homogenized in an industrial scale blender. Duplicate samples (25 g each) of the five individual biomasses and the inoculum were weighed, dried at 105 °C for 24 h, weighed again, ignited for four hours at 550 °C and finally weighed again to calculate the dry matter (DM) and volatile solids (VS) content, respectively. Additional measurements of pH and NH_3/NH_4^+-N (using a Technicon TRAACS-800) were conducted on duplicate biomass samples diluted 10 times with demineralized water. This procedure was repeated each time fresh biomasses and inoculum were collected. All biomasses and inoculum were collected at the same sources throughout the experimental period. An overview of the average characteristics of the five biomasses and inoculum used over the 9 month experimental period is given in Table 1.

2.2. Sample preparation

A total of 95 biomass mixes with different proportions of the five initial biomasses were considered. The selection of biomass mix compositions was random based on raw mass although with emphasis on ternary biomass mixes to facilitate comparison with