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Role of gas accumulation in dry anaerobic digestion of wheat straws

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Abstract

In dry anaerobic digestion, biogas production is inhibited at high total solids contents. Such inhibition can likely be due to a slow diffusion of dissolved molecules into the digestate with subsequent local accumulation of inhibitory products.

In this study, we investigated the impact of H₂ and CO₂ partial pressure on dry AD. Specific batch tests operated were carried out with thin layer to limit gas diffusion. Results showed that initial H₂ partial pressure higher than 800 mbars had a strong inhibitory effect on methane production. The total substrate degradation yields were also impacted, indicating a direct inhibitory effect on hydrolysis. Interestingly, when H₂ and CO₂ were both added, they were consumed by homoacetogenesis/methanogenesis until CO₂ was completely exhausted. CO₂ was found to be the limiting element in case of H₂ inhibition. The reversibility of H₂ inhibition was also investigated by adding CO₂ at different reaction times. Results showed that hydrolysis and methanogenesis inhibitions were fully reversible after CO₂ addition even after 18 days of operation.

Our results give new insights on probable effect of local gas accumulation in dry AD processes.

Keywords

Biogas; Lignocellulosic residues; High solids; Dry anaerobic digestion; Gas transfer

INTRODUCTION

Over the past ten years, Dry Anaerobic Digestion (D-AD) has gained a wide interest in Europe especially when using agricultural waste or the organic fraction of municipal waste. In AD process, the organic matter contained in the waste is converted by anaerobic bacteria into a biogas composed of CH₄ (50-70%) and CO₂ (30-50%). The remaining organic matter is called “digestate” and can be further reused on land as fertilizer after considering sanitary and environmental impacts.

The key parameter that drives microbial processes in D-AD (>15% of total solids TS) is the low water content since microbial end-products could locally accumulate and inhibit methanogenesis (Abbassi-Guendouz et al., 2012).

Water availability depends on two forms: (1) the low available “bound water” where the water is chemically and physically bound to the substrate and (2) the high available “free water” where water can diffuse within the matrix to the microorganisms as well as organic substrates (Pommier and Chenu, 2007). When the total solids (TS) content increases, the quantity of free water decreases with a strong modification of the rheological behaviour of the substrate (García-Bernet et al., 2011). Thus, the transport of soluble compounds within the substrate can become a limiting factor (Bollon et al., 2013). Increasing the TS content usually leads to a reduction of hydrolysis and substrate degradation with a subsequent decrease in biogas production (Abbassi-Guendouz et al., 2012; García-Bernet et al., 2011; Motte et al., 2013). As an illustration, by increasing the TS content from 20 to 30%, Fernández et al. (2008) observed a decrease of organic waste degradation by 17%. At a TS higher than 30%, methane production was strongly inhibited by VFAs accumulation and decrease of pH (Abbassi-Guendouz et al., 2012).

Overall, the limitation of D-AD at high TS might be explained by the slow diffusion of dissolved molecules inside the organic matrix, generating a local accumulation of inhibitory products for methanogens at microbial scale (Martin, 2001; Staley et al., 2011). The inhibitory fermentative by-products could be not only Volatile Fatty Acids (VFAs) (Staley et al., 2011) but also dissolved

gases such as hydrogen (Abbassi-Guendouz et al., 2012). In a recent study, Abbassi-Guendouz et al. (2012) suggested that methanogenesis inhibition at solids content higher than 30% was likely caused by mass transfer limitation and more particularly by a local accumulation of fermentative gases, such as H₂ and CO₂, leading to further VFAs accumulation.

The aim of this study was to investigate the inhibitory effect of dissolved gases on D-AD and especially H₂ and CO₂, since they are both produced by acidogenesis. Batch experiments were designed and carried out to evaluate specifically the effect of H₂ and/or CO₂ partial pressure on methanogenesis in D-AD system.

MATERIAL AND METHODS

Batch experiments were carried out in four replicates during 13 days, with wheat straw as substrate at 25% TS, pH fixed at 8, and substrate/inoculum ratio of 3 (Volatile Solids basis). After inoculation and moisture content adjustment, a thin layer (< 1 cm) of 1 mm meshed wheat straw was first placed at the bottom of the flasks to avoid the effect of gas diffusion within the matrix. Different initial partial pressure of gas (H₂, CO₂ and H₂/CO₂ mixture) were applied: from 0 to 1 530 mbars of H₂, from 0 to 1 982 mbars of CO₂, and H₂/CO₂ mixture with H₂ and CO₂ ranging from 0 to 1 042 mbars and 0 to 433 mbars, respectively.

In a second part, another set of experiments was carried out by adding initially 1 000 mbars of H₂ and further addition of 400 mbars of CO₂ after different times of operation (11 and 18 days).

The medium was buffered and no pH variation was observed. The biogas was measured periodically throughout the experiments. The quantities of VFAs were measured at the start, before adding CO₂ and at the end of each experiment.

MAIN RESULTS

Specific H₂ inhibition of methanogenesis and hydrolysis in D-AD

From 0 to 600 mbars of initial H₂, a slight increase of CH₄ production was observed from 25.2 ± 3.5 mL CH₄/g_{VS} in the controls to 39.6 ± 4.9 mL CH₄/g_{VS}. Such increase was due to the consumption of H₂ added initially. At higher initial p_{H₂}, the cumulative production of CH₄ decreased from 39.6 ± 4.9 mL CH₄/g_{VS} for an initial p_{H₂} of 600 mbars down to 8.45 ± 1.46 mL CH₄/g_{VS} for an initial p_{H₂} of 1 555 mbars., with a transition phase between 650 and 800 mbars. Therefore, an initial p_{H₂} higher than 800 mbars induced a strong and stable inhibition of methanogenesis at TS content of 25%.

No accumulation or significant change in VFAs was observed whatever the initial p_{H₂}, and inhibition of the methanogenesis step was also not related to a pH decrease. In addition, the acetogenesis was not inhibited and no other metabolic pathways were found for a high p_{H₂} like for example a production of butyrate or caproate (Arslan et al., 2012). Therefore, VFA accumulation or changes in pattern cannot explain the observed methanogenesis inhibition, as previously shown in wet AD (Ahring and Westermann, 1988; Amani et al., 2010; Siegert and Banks, 2005).

When considering the total amount of metabolic products (VFAs, H₂), the total substrate degradation rate (Figure 1) decreased according to the initial p_{H₂}. Since no sugars were accumulated in the bulk phase, these results suggest a strong inhibition of hydrolysis at initial partial pressure of H₂ higher than 800 mbars. It is well known that hydrolysis is the limiting step in D-AD (Pavlostathis and Giraldo-Gomez, 1991) and the composition of the substrate (morphological and chemical) can have a strong effect on this step, especially the quantity of lignin for lignocellulosic wastes (Monlau et al., 2012). The present study clearly shows for the first time a strong inhibition of hydrolysis by H₂ partial pressure in D-AD.

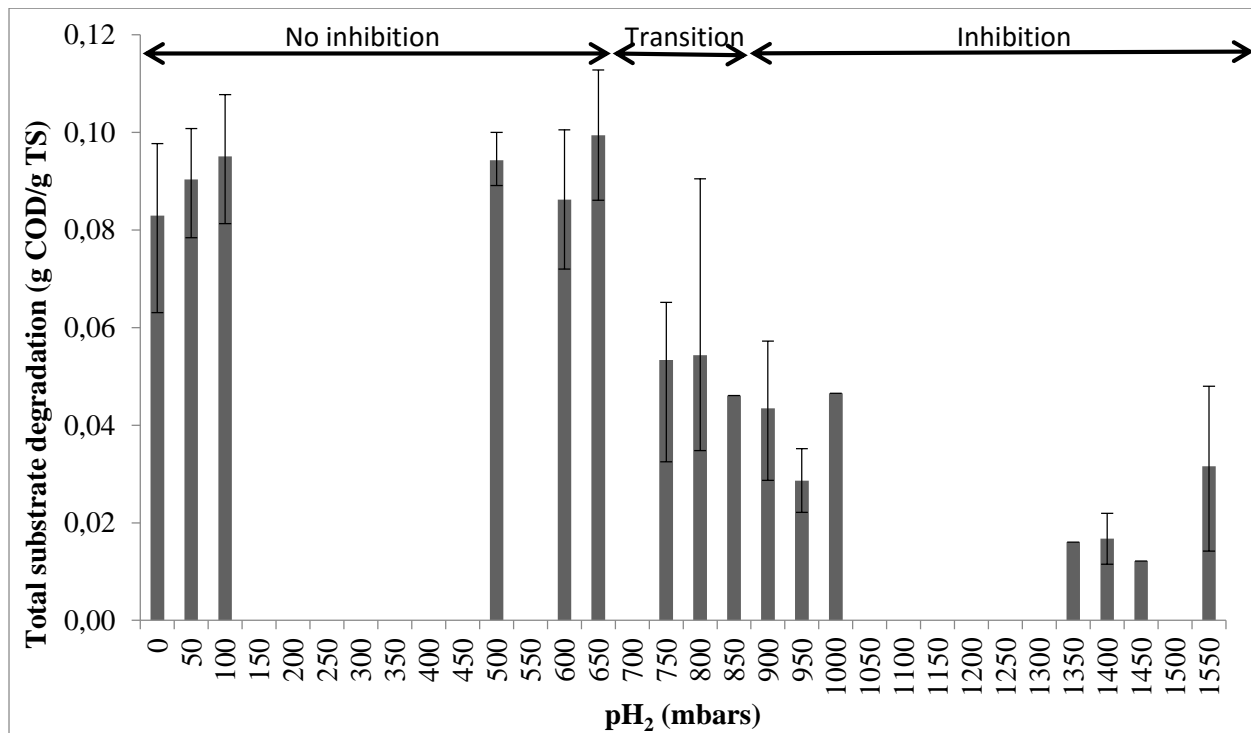


Figure 1: Substrate degradation (g COD at the end/g TS –g COD at the beginning/g TS) according to the initial partial pressure of H₂ in mbars at 25% of TS, 35°C and pH 8. TS: Total Solids; COD: Chemical oxygen demand.

Interestingly, at low initial p_{H_2} , H₂ was totally converted to acetate and methane. At an initial p_{H_2} higher than 750 mbars, H₂ was not fully consumed and H₂ remained in headspace at the end of the experiments. From 750 to 1 000 mbars, a part of initial H₂ was used to produce acetate by homoacetogenesis (Montero et al., 2009) but H₂ was not totally consumed since some H₂ remained at the end of the experiment. CO₂ accumulation was also monitored and at a p_{H_2} ranging from 0 to 750 mbars, CO₂ was produced due to the microbial activity and a decrease of the released CO₂ was observed from 38.98 ± 10.45 to 15.33 ± 2.3 ml CO₂ /g_{VS} in the controls and at 750 mbars of p_{H_2} respectively. Over 750 mbars, no CO₂ was accumulated in the headspace. Since the increase of the remaining amount of H₂ in headspace was correlated to a decrease of remaining CO₂, it was concluded that CO₂ production was the limiting factor for further H₂ consumption (Florin and Harris, 2008). This hypothesis was tested by adding both CO₂ (400 mbars) and H₂ (1 000 mbars) at the start of the experiment. After correcting methane production by the methane produced using the added gases, methane production was similar in the mixture of H₂/CO₂ and in the control. Therefore, in that case, no methanogenesis inhibition occurred. These results confirm that CO₂ production can be considered as the limiting factor when p_{H_2} is high.

Reversibility of the H₂ inhibition in D-AD

Since adding CO₂ can prevent the H₂ inhibition of hydrolysis and methanogenesis, we investigated the reversibility of the H₂ inhibition by introducing CO₂. An inhibitory p_{H_2} of 1 000 mbars was added at the start of the experiment and CO₂ (400 mbars) was further added at different times (11 and 18 days) to test the reversibility of the inhibition.

For both experiments, H₂ inhibition stopped after CO₂ addition. The profiles of cumulated production of CH₄ after adding the CO₂ shows: (1) a rapid increase of CH₄ production mainly due to H₂ and CO₂ consumption, (2) a short lag phase with a slower production of CH₄ and (3) a constant and stable CH₄ production and substrate degradation as observed in the control. These last

experiments clearly showed the reversibility of hydrolysis inhibition by H₂.

CONCLUSION

This study provides new insight about the effect of fermentative gases and more particularly H₂, on D-AD when using wheat straw as substrate. By adding CO₂, hydrolysis inhibition by H₂ was not only suppressed but was also fully reversible. This indicates that CO₂ could be a limiting factor in D-AD when inhibition by H₂ occurs. Our results were however obtained with a thin layer substrate to avoid the effect of the gas diffusion. In real D-AD digesters, combined effects of inhibition as well as gas diffusion can occur. Nevertheless, hydrolysis inhibitory effect of H₂ can take place at a local scale, and may be one of the main reasons of the decrease in overall digester performances in D-AD.

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