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Performance and stability of sewage sludge digestion under CO_2 enrichment: A pilot study

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ABSTRACT

Carbon dioxide (CO_2) injection in anaerobic digestion has recently been proposed as an interesting possibility to boost methane (CH_4) recovery from sludge and organic waste by converting a greenhouse gas into a renewable resource. This research assessed the effects of exogenous CO_2 injection on performance and process stability of single-phase continuous anaerobic digesters. Two pilot scale reactors treating sewage sludge were operated for 130 days. One reactor was periodically injected with CO_2 while the other acted as control. Two injection frequencies and injection devices were tested. The results indicated that CO_2 enrichment allowed an increase in CH_4 production of *ca.* 12%, with a CH_4 production rate of 371 ± 100 L/(kgVS$_{fed}$·d) and a CH_4 concentration of *ca.* 60% when dissolved CO_2 levels inside the test reactor were increased up to 1.9-fold. Results also indicated an improvement in process resilience to temporary overloads and no impacts on stability parameters.

1. Introduction

Anaerobic digestion (AD) has recently been proposed as a promising system to biochemically convert exogenous carbon dioxide (CO_2) into methane (CH_4) (Bajón Fernández et al., 2014; Salomoni et al., 2011) and this option is finding growing interest thanks to the possibility of developing carbon negative renewable energy production (Cheah et al., 2016; Budzianowski, 2012). CO_2 reduction to CH_4 in the AD process is traditionally associated with the activity of hydrogenotrophic methanogens (Demirel and Scherer, 2008). Homoacetogens can also play a role in reducing CO_2 and H_2 into acetic acid that is then transformed into CH_4 by acetoclastic methanogens (Liu et al., 2016) or through syntrophic acetate oxidation followed by hydrogenotrophic methanogenesis (Schnürer and Nordberg, 2008). Whilst the biochemical mechanisms for exogenous CO_2 bioconversion in AD have not been fully elucidated, various authors have assessed the possibility to enhance CH_4 production from AD by CO_2 enrichment. Alimahmoodi and Mulligan (2008) studied, at lab scale, the possibility of converting CO_2 into CH_4 by using an up-flow anaerobic sludge blanket (UASB) reactor fed with a solution composed of dissolved CO_2 and volatile fatty acids (VFAs). The same authors observed a 69–86% CO_2 uptake, reporting that VFAs were used as source of H_2 for hydrogenotrophic methanogens to perform the CO_2 conversion to CH_4. Salomoni et al. (2011) studied at pilot scale the injection of CO_2 into the fermentation phase of a two-phase anaerobic digestion (TPAD) plant. Off gases from the fermentation phase were recirculated into the methanogenic phase to sustain CO_2 reduction to CH_4 and a 25% increase in CH_4 yield was observed. Similarly, Yan et al. (2016) studied the recirculation of off-gases from a TPAD reactor for food waste digestion. These authors utilised an acidogenic leach bed reactor, as first phase, and diverted off-gases (rich in CO_2 and H_2) and leachate from this reactor into a methanogenic UASB, used as second digestion phase. Results indicated an improvement of CH_4 production thanks to CO_2 and H_2 conversion to CH_4 that was assumed to be carried out by hydrogenotrophic methanogens.

These results highlight the biological feasibility of CO_2 bioconversion into CH_4 even though most of the studies utilised exogenous H_2 to support this bioprocess. The current lack of an inexpensive H_2 supply system and the low water solubility of H_2 are challenges that hinder the full exploitation of CO_2 bioconversion into CH_4 at AD sites by the use of exogenous H_2 (Bassani et al., 2016). Similarly, the use of TPAD configuration could limit a large implementation of CO_2 bioconversion, considering that the majority of AD assets are single phase plants (De Baere and Mattheeuws, 2010).

To overcome these limitations, an alternative approach could be

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based on the injection of CO_2 directly into digesters without any additional fermentation phase and without addition of exogenous H_2. Recent studies have assessed this procedure and indicated encouraging results. Bajón Fernández et al. (2014) studied the possibility to improve AD performance by direct CO_2 injection in single phase digestion, without the availability of exogenous H_2. Results from batch tests indicated an increase of CH_4 yields between 5% and 13% for food waste digestion and a speed up of CH_4 production for sewage sludge leading to an increase of *ca.* 100% on CH_4 production within the first 24 h of digestion, if compared to control experiments. A positive influence of exogenous CO_2 on AD performance during biochemical methane potential (BMP) tests was also reported by Koch et al. (2015, 2016), that observed an increase of CH_4 yields proportional to the CO_2 concentration of gases used to flush the reactors' head space. The benefit of direct injection of CO_2 on AD was also observed at pilot scale for food waste digestion (Bajón Fernández et al., 2015). Results from this investigation indicated a 2.5-fold increase in H_2 concentration in the digester enriched with CO_2, that could support the conversion of exogenous CO_2 into CH_4, and resulted in a *ca.* 20% higher CH_4 production when comparing performance of test reactor before and after CO_2 injection.

These results therefore support that biochemical conversion of exogenous CO_2 to CH_4 can be obtained in AD also without external supplementation of H_2. This option opens the possibility to exploit such biological process in various industrial sectors where AD is already an implemented technology. This could be further facilitated by the growing application of biogas upgrading to biomethane (Sun et al., 2015) that is leading to the large availability of CO_2, directly on the digestion sites, that can be converted into CH_4, as promising approach to convert a waste stream into a commodity (Koch et al., 2016).

Enhancement of CH_4 production from sewage sludge AD supplemented with exogenous CO_2 has only been proved at batch scale (Bajón Fernández et al., 2014) and further confirmations at larger scale are needed to proof the concept and clarify the long-term impacts of CO_2 injection on AD performance and stability. This research was therefore aimed at assessing, at pilot scale, the effects of exogenous CO_2 injection on single phase continuous AD of sewage sludge, without exogenous H_2 addition. The research focused on understanding the impacts of moderate and intense exogenous CO_2 injections on CH_4 production, biogas quality and AD process stability parameters.

2. Material and methods

2.1. Reactors configuration and operation

Two identical pilot scale AD reactors were used for the research study. The reactor used for CO_2 enrichment is hereafter referred to as Test reactor while the other is referred to as Control reactor. A scheme of the experimental rig is presented in Fig. 1. Each unit was composed of a cylindrical reactor with a cone base having a total volume of 165 L. Working liquid volume was set to 90 L. Mixing of digestion material was performed by an external peristaltic pump (series 600, Watson Marlow, Cornwall, UK). Pump rate was set to have a full recirculation of the working liquid volume in 30 min. The AD process was carried out at mesophilic conditions. Temperature of digestion liquid was maintained at 38.5 ± 1 °C by using heating jackets (LMK Thermosafe, Haverhill, UK) placed over the cylindrical section of each reactor.

The reactors were operated semi-continuously with feeds carried out once a day. The feeding regime was repeated weekly as follows: 6 L of sewage sludge from the 1st to the 4th day of the week, 12 L of sewage sludge on the 5th day and no feed on the 6th and 7th day of the week. Micronutrients were added during any feed at a dosing rate of 0.05 mL of TEA 310 solution (Omex Environmental Ltd., King's Lynn, UK) per kg of volatile solids (VS) fed. The pH of feeding sewage sludge was not adjusted. The weekly average Hydraulic Retention Time (HRT) was 17.5 d and the average Organic Loading Rate (OLR) was 2.1 ± 0.4 kgVS/(m^3·d). The two reactors were fed in parallel at the same time of the day and were maintained at the same feeding conditions for the entire experimental period.

The Test reactor was equipped with an external column retrofitted as a side process to perform the CO_2 enrichment of the digestion liquid. The column was connected to the Test reactor in the mixing loop only during each CO_2 enrichment (Fig. 1). Test and Control reactors operated similarly during the rest of the time. No CO_2 injections were carried out on Test reactor until day 42.

Biogas production, biogas composition, pH and temperature of the digestion liquid were monitored five times per week. Samples of digestate from both reactors were collected up to 5 times a week to measure: Total Solid (TS), VS, Ammonium Nitrogen (NH_4^+), Partial Alkalinity (PA), Intermediate Alkalinity (IA), Total Alkalinity (TA), H_2CO_3 Alkalinity and total Volatile Fatty Acids (VFAs) concentration.

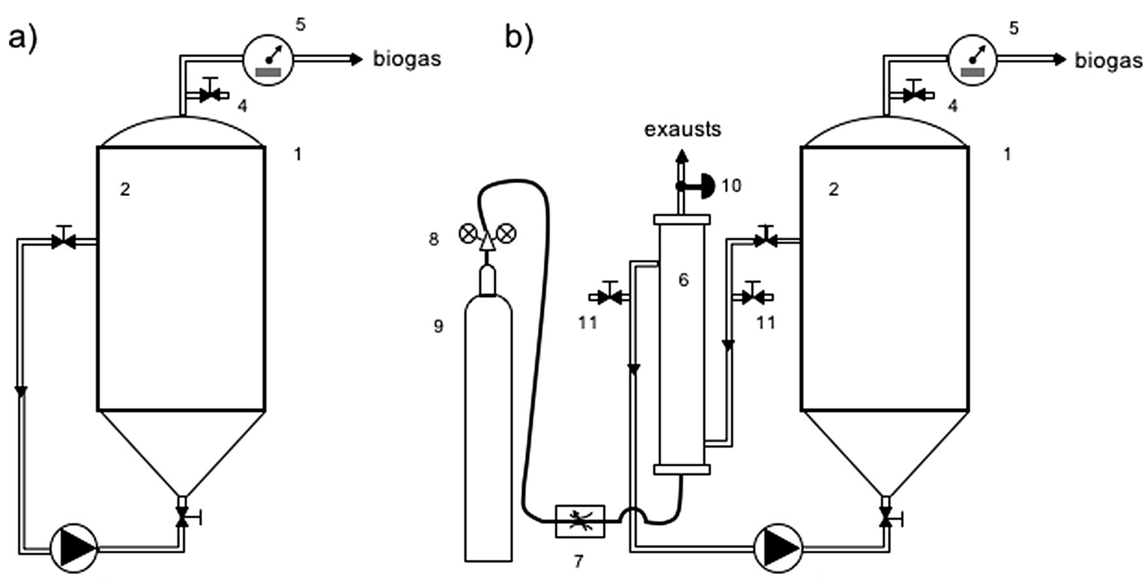

Fig. 1. Scheme of the experimental rig. (a) Control reactor and (b) Test reactor configuration during CO_2 injection. (1) Anaerobic reactor, (2) heating jacket, (3) peristaltic pump, (4) biogas sample point, (5) biogas meter, (6) bubble column, (7) mass flow controller, (8) gas pressure regulator, (9) CO_2 cylinder, (10) CH_4-CO_2 analyser, (11) digestate sampling point.