IMPROVING ANAEROBIC DIGESTION BY CARBON DIOXIDE ENRICHMENT: INCREASING BIOGAS PRODUCTION AND CARBON DIOXIDE UPTAKE

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Abstract

Carbon dioxide (CO₂) enrichment may be applied in anaerobic digestion (AD) to improve methane generation and to obtain a ‘closed loop’ AD process through carbon sequestration by using the CO₂ stream produced during biogas upgrading. Methane yield increases of 30% and 40% CO₂ uptake during sewage sludge digestion have previously been reported. In this study nitrogen and CO₂ (g) were diffused initially into water to quantify the time required to reach CO₂ saturation conditions with the diffusers in place (2 mins for injections of 1Lpm and 0.5 CO₂ molar fraction). The CO₂ was then diffused into batch anaerobic digesters (1 L volume) at different molar fractions of CO₂ (0.3, 0.6 and 0.9) containing food waste material to determine the benefits for biogas production, CO₂ uptake and solids reduction during digestion. Enhancements in the renewable energy production were obtained, reaching 13% increased methane yields when enriching the digestion process with CO₂ at 0.9 mole fraction. Associated reductions regarding the overall CO₂ emissions of around 11% were observed, thus proving the potential of AD to act as a carbon sink when treating food waste material. Any initial acidification due to CO₂ enrichment was buffered during the digestion process. Therefore, the CO₂ could be injected periodically, which could further enhance the observed benefits in terms of methane production and carbon uptake.

Key words

anaerobic digestion, carbon capture, CO₂, CH₄, food waste, optimisation.

Introduction

Anaerobic digestion (AD) is the most widespread management solution for sewage sludge with increasing application for food waste. The majority of previous studies which have aimed to improve AD have focused on increasing the biodegradability of the input material rather than on the optimisation of the digester operation itself. These studies have led to the development of sludge pre-treatments which can have high parasitic energy demands and varying levels of success in terms of soluble chemical oxygen demand (sCOD) and volatile fatty acid (VFA) release.

Few studies have assessed the potential of optimising anaerobic processes by enriching the reactor or the input material to be treated with carbon dioxide (CO₂). As early as 1994, (Sato & Ochi 1994) stated associated benefits of up to 30% increased specific methane yields when enriching with CO₂ AD treating sewage sludge. Salomoni et al. (2011) and Alimahmoodi & Mulligan (2008) further confirmed the potential of CO₂ biological conversion in anaerobic processes: two-phased anaerobic digesters (TPAD) and Upflow Anaerobic Sludge Blanket (UASB) reactors respectively.

A transformation of CO₂ into CH₄ in anaerobic processes considers the carbon as a raw material rather than as a waste, and the digesters themselves as carbon sinks in which the CO₂ is utilised rather than stored as in the conventional CO₂ capture and storage (CCS) techniques. Further benefits
are envisaged if the increasing implementation of biogas upgrading technologies is considered, which leads to a waste stream concentrated in CO$_2$ whose use in the CO$_2$ enrichment technology could lead to a ‘closed CO$_2$ loop’ for the AD process.

A wide implementation of the CO$_2$ enrichment technology may have significant benefits over conventional AD optimisation technologies since it could be potentially implemented without high operational or capital costs. For example, relatively low capital investments could be required if the CO$_2$ was introduced in the recirculation or feed stream rather than in the digester itself or if current gas mixing systems could be adapted for the CO$_2$ injection.

This paper examines the potential of CO$_2$ enrichment as a possible way of increasing CH$_4$ production during food waste digestion. For this purpose one litre batch AD units were operated after saturating the food waste material to digest with four different CO$_2$ molar fractions (0, 0.3, 0.6 and 0.9). The methane production, digestate quality and carbon uptake were subsequently examined.

**Materials and methods**

*Experimental rig and gas injection*

Methane potential tests were conducted using laboratory scale batch AD units. Each digester consisted of a one litre glass bottle (Fisher Scientific, Loughborough, United Kingdom) with a GLS80 four port cap (Fisher Scientific, Loughborough, United Kingdom). Two ports were used for gas injection by means of Pyrex diffusers with a porosity of 3 and 15 mm diameter in the diffusion end (Fisher Scientific, Loughborough, United Kingdom). One port was blocked with a 17mm septa (Thames Restek UK Ltd., Buckinghamshire, United Kingdom) allowing gas sample extraction for composition analysis and the last port was the biogas exit connected to a MilliGascounter (Litre Meter Ltd., Buckinghamshire, United Kingdom) for volume recording. The digesters were placed in a temperature controlled water bath (38±0.5°C) and continuously stirred by magnetic stirrers. Additionally, the units were stirred more vigorously once per day.

Eight digesters were set up, each of them inoculated with digested food waste and fed with macerated food waste as the substrate, both collected from a full scale food waste digestion plant in the United Kingdom. The digesters were set up with an inoculum to substrate volatile solids (VS) ratio of 2:1 and a total working volume of approximately 700 ml was maintained.

![Figure 1: Representation of the rig used for the methane potential tests.](image-url)
The sludge in each digester (mixtures of seed and feed) was saturated with CO\(_2\) at different molar fractions before starting the digestion process. Figure 1 represents the system used. The N\(_2\)\((g)\) and CO\(_2\)\((g)\) streams were supplied from gas cylinders (BOC, Manchester, United Kingdom) and were controlled by Mass Flow Controllers (MFC) (Premier Control Technologies, Norfolk, United Kingdom). Both streams were mixed before being split again and injected through the two diffusers. The mass transfer was encouraged by continuously stirring the content of the digester during the gas injection.

In order to ensure saturation conditions were reached, a safety factor of at least ten was applied with respect to the results of some preliminary saturation tests developed with deionized (DI) water, in which it was concluded that saturation with CO\(_2\) could be achieved in less than two minutes with the diffusers in place. Therefore, all the digesters were bubbled for at least 20 minutes.

The digesters were operated in duplicate, at four different CO\(_2\) molar fractions: 0, 0.3, 0.6 and 0.9. In the two control reactors pure N\(_2\)\((g)\) (CO\(_2\) molar fraction equal to 0) was bubbled through for up to 20 minutes to ensure anaerobic conditions and that any methane enhancement observed in the test reactors was not a result of improved mixing due to additional gas. The partial pressures associated with these molar fractions were obtained with the pressure and temperature of the incoming streams (CO\(_2\) and N\(_2\)) recorded from the display of the MFCs. The CO\(_2\) injection conditions used for each replicate were as stated in Table 1.

### Table 1: CO\(_2\) injection conditions for each batch anaerobic reactor treating food waste.

<table>
<thead>
<tr>
<th></th>
<th>*(D(_{0.3}))(_1)</th>
<th>*(D(_{0.3}))(_2)</th>
<th>*(D(_{0.6}))(_1)</th>
<th>*(D(_{0.6}))(_2)</th>
<th>*(D(_{0.9}))(_1)</th>
<th>*(D(_{0.9}))(_2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>volumetric flow rate N(_2) (Lpm)**</td>
<td>1.00</td>
<td>0.70</td>
<td>0.40</td>
<td>0.10</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>mass flow rate N(_2) (sLpm)**</td>
<td>1.32</td>
<td>0.69</td>
<td>0.51</td>
<td>0.20</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>T N(_2) (°C)</td>
<td>25.01</td>
<td>22.37</td>
<td>19.84</td>
<td>18.79</td>
<td>19.84</td>
<td></td>
</tr>
<tr>
<td>p(_{N2}) (psia)</td>
<td>19.41</td>
<td>23.50</td>
<td>24.53</td>
<td>24.63</td>
<td>24.78</td>
<td></td>
</tr>
<tr>
<td>moles N(_2)/min</td>
<td>0.05</td>
<td>0.05</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>volumetric flow rate CO(_2) (Lpm)</td>
<td>0.00</td>
<td>0.30</td>
<td>0.60</td>
<td>0.79</td>
<td>0.79</td>
<td></td>
</tr>
<tr>
<td>mass flow rate CO(_2) (sLpm)</td>
<td>0.00</td>
<td>0.29</td>
<td>0.41</td>
<td>0.77</td>
<td>1.53</td>
<td></td>
</tr>
<tr>
<td>T CO(_2) (°C)</td>
<td>n/a</td>
<td>22.37</td>
<td>23.13</td>
<td>23.31</td>
<td>25.09</td>
<td></td>
</tr>
<tr>
<td>p(_{CO2}) (psia)</td>
<td>n/a</td>
<td>19.87</td>
<td>21.00</td>
<td>28.81</td>
<td>22.48</td>
<td></td>
</tr>
<tr>
<td>moles CO(_2)/min</td>
<td>n/a</td>
<td>0.02</td>
<td>0.03</td>
<td>0.06</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Injected yCO(_2)</td>
<td>n/a</td>
<td>0.30</td>
<td>0.60</td>
<td>0.89</td>
<td>0.89</td>
<td></td>
</tr>
<tr>
<td>Injected p(_{CO2}) (bar)</td>
<td>n/a</td>
<td>0.48</td>
<td>0.78</td>
<td>1.76</td>
<td>1.37</td>
<td></td>
</tr>
</tbody>
</table>

*In this table the nomenclature is as follows:
- D\(_C\): digester control
- D\(_{0.3}\): digester enriched with CO\(_2\) at 0.3 molar fraction (analogous for the rest of molar fractions)
- The subscript outside the brackets indicates the number of replicate
- yCO\(_2\): CO\(_2\) molar fraction
- p\(_{CO2}\): CO\(_2\) partial pressure (analogous for nitrogen)

** Volumetric flow rate at standard conditions (1 atm and 25°C)

### Analytical methods

The sludges were analysed on commencement and end of the AD operation for pH, total solids (TS) and VS. The concentration of TS and VS was quantified according to the standard methods 2540B and 2540E respectively (APHA, 2005).
The biogas volume production and CO$_2$-CH$_4$ content were recorded daily by means of MilliGascounters (Litre Meter Ltd., North Marston, United Kingdom) and a CSi 200 Series Gas Chromatograph (Cambridge Scientific Instruments Ltd., Witchford, United Kingdom) with a dual column, respectively. The digesters’ content was agitated prior to each sample collection.

**Determination of CO$_2$ utilisation during digestion**

A continuously fed anaerobic digester can be modelled as a continuous stirred tank reactor in which the region considered as the control volume is the liquid phase. With this approach the following mass balance was obtained:

![Schematic diagram](image)

**Figure 2:** Schematic of the inputs and outputs considered for the CO$_2$ mass balance.

Initial assumptions:

1) Isothermal
2) Perfectly mixed reactor (enough mix to consider uniform concentration inside the reactor, which is equal to the outlet concentration)
3) The control volume, $V$, is established in the fluid phase and considered to be constant. In a more accurate approach the variability of liquid phase due to the change of VS between phases could be considered.

$$\text{inlet} - (\text{outlet}_1 + \text{outlet}_2) + \text{production} - \text{consumption} = \text{accumulation}$$

$$(F_{\text{CO}_2})_0 - (F_{\text{CO}_2})_1 - (F_{\text{CO}_2})_2 + \sum_{i=0}^{i=n}(R_{\text{CO}_2})_i \cdot V = \frac{dN_{\text{CO}_2}}{dt}$$  \hspace{1cm} \text{(Eq. 1)}$$

Where:

- $(F_{\text{CO}_2})_0$: flow rate of CO$_2$ incoming the digester dissolved in the feed material (mol/s)
- $(F_{\text{CO}_2})_1$: flow rate of CO$_2$ exiting the digester dissolved in the digested material (mol/s)
- $(F_{\text{CO}_2})_2$: flow rate of CO$_2$ exiting the digester with the biogas (mol/s)
- $\sum_{i=0}^{i=n}(R_{\text{CO}_2})_i \cdot V$: term accounting for the production and consumption of CO$_2$ in the digester (mol/s)
- $(R_{\text{CO}_2})_i$: reaction rate considered as positive for production and negative for consumption (mol/(s·m$^3$))
- $V$: control volume m$^3$
- $\frac{dN_{\text{CO}_2}}{dt}$: CO$_2$ accumulation in the digester per time (mol/s)
When steady state operation is considered (stable reactor operation, thus the start-up is not modelled) the accumulation term equals zero. Therefore the mass balance can be modelled as an algebraic equation rather than a differential one:

\[(F_{CO_2})_0 - (F_{CO_2})_1 - (F_{CO_2})_2 + \sum_{i=0}^{n}(R_{CO_2})_i \cdot V = 0 \text{ (Eq. 2)}\]

Because of the complexity of the reactions taking place in an anaerobic digester, the kinetic properties of each of them cannot be determined. However, the reaction term can be considered as a gathering of all the individual reaction contributions which represents the total uptake or production of CO\(_2\) in the system.

\[(F_{CO_2})_0 - (F_{CO_2})_1 - (F_{CO_2})_2 = -\sum_{i=0}^{n}(R_{CO_2})_i \cdot V \text{ (Eq. 3)}\]

Since the reaction rate is considered to be positive for production and negative for consumption, a positive \(-\sum_{i=0}^{n}(R_{CO_2})_i \cdot V = (CO_2)_{removed}\) term would imply a CO\(_2\) uptake in the anaerobic digester.

\[(F_{CO_2})_0 - (F_{CO_2})_1 - (F_{CO_2})_2 = (CO_2)_{removed} \text{ (Eq. 4)}\]

This general mass balance can be applied to the batch anaerobic digesters tested by considering the initial CO\(_2\) dissolved in the reactor content rather than a continuous input with the feed, and the amount of CO\(_2\) dissolved in the final digestate rather than a continuous output.

The main assumptions for obtaining all the terms of this mass balance from the laboratory data are:
- The efficiency of the mass transfer was not considered (CO\(_2\) in the system when saturation conditions are reached, not the CO\(_2\) required to reach this state).
- Considered 1 mol = 24 L for calculating the mass of CO\(_2\) emitted with the biogas. Therefore, the gas outlet of the MilliGascounters was assumed to be at 20°C and 1atm.
- Density and Henry’s constant same as for water.
- The solids reduction was not considered when calculating the CO\(_2\) dissolved in the digestates.
- Percentage of recovery in the headspace tests equal to 100%.

**Results**

*Renewable energy enhancement*

It can be observed (Figure 3 and Figure 4) that the cumulative biogas and methane production of all the digesters enriched with CO\(_2\) was significantly higher than that of the controls (the results are presented as averages between replicates). Those reactors bubbled with gas with \(y_{CO_2}=0.9\) obtained the highest methane yields while the biogas performance for those with \(y_{CO_2}=0.3\) and \(y_{CO_2}=0.6\) was similar. When the cumulative methane production is considered, the highest benefit was obtained when enriching with \(y_{CO_2}=0.9\), followed by 0.3 and 0.6.
Figure 3: Cumulative total biogas production ($\text{CH}_4$ and $\text{CO}_2$) normalised per VS of the food waste to be digested (mixture of feed and seed). The data are averaged between replicates and the error bars represent the difference of the actual values to the mean. The nomenclature is DC: digester control ($\text{CO}_2$ molar fraction equal to 0), D0.3: digester enriched with $\text{CO}_2$ at 0.3 molar fractions and analogous for the rest of molar fractions.

Figure 4: Cumulative methane production normalised per VS of the food waste to be digested (mixture of feed and seed). The data are averaged between replicates and the error bars represent the difference of the actual values to the mean.
**Digester performance (pH, TS and VS reduction)**

Table 2 outlines the characterization of the material digested in terms of pH, TS and VS. A single initial CO$_2$ injection did not have a significant effect in the VS or TS reduction. In addition, there was not a substantial change in the final pH of the different digesters, which may mean that any initial pH alteration caused by the CO$_2$ injection was compensated later on during the digestion process.

**Table 2:** Comparison of the food waste (mixture of feed and seed) before and after the digestion process in terms of pH, TS and VS. The input data are before saturating the material with CO$_2$.

<table>
<thead>
<tr>
<th></th>
<th>DC</th>
<th>D$_{0.3}$</th>
<th>D$_{0.6}$</th>
<th>D$_{0.9}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>pH input</td>
<td>7.64</td>
<td>7.64</td>
<td>7.64</td>
<td>7.64</td>
</tr>
<tr>
<td>pH digestate</td>
<td>8.38</td>
<td>8.39</td>
<td>8.38</td>
<td>8.39</td>
</tr>
<tr>
<td>TS input (mg/g)</td>
<td>56.63</td>
<td>56.63</td>
<td>56.63</td>
<td>56.63</td>
</tr>
<tr>
<td>TS digestate (mg/g)</td>
<td>47.23</td>
<td>46.91</td>
<td>47.55</td>
<td>46.84</td>
</tr>
<tr>
<td>TS reduction (%)</td>
<td>16.6</td>
<td>17.2</td>
<td>16.0</td>
<td>17.3</td>
</tr>
<tr>
<td>VS input (mg/g)</td>
<td>36.86</td>
<td>36.86</td>
<td>36.86</td>
<td>36.86</td>
</tr>
<tr>
<td>VS digestate (mg/g)</td>
<td>27.22</td>
<td>27.44</td>
<td>27.51</td>
<td>27.28</td>
</tr>
<tr>
<td>VS reduction (%)</td>
<td>26.1</td>
<td>25.6</td>
<td>25.4</td>
<td>26.0</td>
</tr>
</tbody>
</table>

**CO$_2$ emissions reduction**

Each of the terms required for the mass balance equation (Eq. 4) was obtained as follows:

1) (F$_{CO2}$)$_0$: amount of CO$_2$ initially dissolved in the material to be digested

According to (Green & Perry 2008) at 38.5°C the solubility in mole fraction of CO$_2$ (g) in water is 4.417E-4 when the CO$_2$ partial pressure is 1 atm (Henry’s constant of H=2264 atm). Considering the density of water at 38.5°C to be 992.74 kg/m$^3$, an equilibrium concentration of dissolved CO$_2$ of 1071 mg CO$_2$ · L$^{-1}$ is expected. If a different CO$_2$ partial pressure is used for saturating, the solubility will change according to Henry’s law. Thus, the amounts of dissolved CO$_2$ under saturation conditions with the different partial pressures used in the laboratory experiments and a working volume of food waste of 700 ml are those included in Table 3.

**Table 3:** Data for calculation of the amount of CO$_2$ dissolved in each batch anaerobic reactor under saturation conditions and final calculated values. Data are averaged between replicates.

<table>
<thead>
<tr>
<th></th>
<th>DC</th>
<th>D$_{0.3}$</th>
<th>D$_{0.6}$</th>
<th>D$_{0.9}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y$_{CO2}$</td>
<td>0.00</td>
<td>0.30</td>
<td>0.60</td>
<td>0.89</td>
</tr>
<tr>
<td>p$_{CO2}$ Injected</td>
<td>0.00</td>
<td>0.44</td>
<td>0.83</td>
<td>1.57</td>
</tr>
<tr>
<td>Dissolved CO$_2$ concentration (mg/L) by Henry and Dalton's law</td>
<td>0.0</td>
<td>475.9</td>
<td>884.5</td>
<td>1678.7</td>
</tr>
<tr>
<td>Dissolved CO$_2$ in 700 ml of material to digest (mg)</td>
<td>0.0</td>
<td>333.2</td>
<td>619.1</td>
<td>1175.1</td>
</tr>
</tbody>
</table>

2) (F$_{CO2}$)$_1$: flow rate of CO$_2$ exiting the digester dissolved in the digested material

This term was obtained by gas chromatography of the headspace created by digestate samples allowed to reach equilibrium conditions. The initial concentrations in the liquid phase were calculated with Henry’s law and are included in Table 4. Single replicates were used for this test.
3) \( (F_{CO2})_2: \) flow rate of \( CO_2 \) exiting the digester with the biogas (mol/s)

This term is the cumulative \( CO_2 \) production calculated with the daily readings of biogas production and \( CO_2 \) concentration and considering 1mmol \( CO_2 = 24 \) mL \( CO_2 \) (20°C and 1 atm). The values for this parameter (average between replicates) are included in Table 4.

4) \( (CO_2)_{removed} \)

According to the previously described mass balance (Eq. 4):

\[
(F_{CO2})_0 - (F_{CO2})_1 - (F_{CO2})_2 = (CO_2)_{removed}
\]

The obtained \( CO_2 \) removed was negative for all the anaerobic digesters, as shown in Table 4, meaning that there was a net \( CO_2 \) generation rather than removal. This was expected since the amount of \( CO_2 \) initially dissolved in the food waste is relatively small in comparison with that generated during the digestion process. However, the net \( CO_2 \) emitted by the test digesters (considering both the inlet and the outlets) was lower than that of the controls, leading to the overall reduction of \( CO_2 \) emissions included in Table 4.

Table 4: Values of each term of the \( CO_2 \) mass balance and calculated reduction of the \( CO_2 \) emissions of the test reactors compared with the controls. The data are averaged between replicates.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>DC</th>
<th>D0.3</th>
<th>D0.6</th>
<th>D0.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>( (F_{CO2})_0 ) (mg)</td>
<td>( CO_2 ) dissolved in the digesting material (mixture of feed and seed)</td>
<td>0</td>
<td>333</td>
<td>619</td>
<td>1175</td>
</tr>
<tr>
<td>( (F_{CO2})_1 ) (mg)</td>
<td>( CO_2 ) dissolved in the digested material</td>
<td>183</td>
<td>233</td>
<td>191</td>
<td>234</td>
</tr>
<tr>
<td>( (F_{CO2})_2 ) (ml)</td>
<td>( CO_2 ) exiting the digester in the biogas</td>
<td>2153.2</td>
<td>2234.8</td>
<td>2271.7</td>
<td>2515.1</td>
</tr>
<tr>
<td>( (F_{CO2})_3 ) (mg)</td>
<td>( CO_2 ) exiting the digester in the biogas</td>
<td>3948</td>
<td>4097</td>
<td>4165</td>
<td>4611</td>
</tr>
<tr>
<td>( (CO_2)_{removed} ) (mg)</td>
<td>( CO_2 ) generated less than control (mg)</td>
<td>-4131</td>
<td>-3996</td>
<td>-3736</td>
<td>-3670</td>
</tr>
<tr>
<td>( CO_2 ) generated less than control (mg)</td>
<td>n/a</td>
<td>134</td>
<td>395</td>
<td>461</td>
<td></td>
</tr>
<tr>
<td>Overall reduction of ( CO_2 ) emissions (% of ( CO_2 ) generated less than control as % )</td>
<td>n/a</td>
<td>3</td>
<td>10</td>
<td>11</td>
<td></td>
</tr>
</tbody>
</table>

Discussion

The findings from the operation of batch one litre anaerobic digesters enriched with \( CO_2 \) and its comparison with control digesters confirmed the potential of the \( CO_2 \) enrichment technology as a possible way of increasing \( CH_4 \) production during food waste digestion with commensurate \( CO_2 \) uptake.

The biogas and methane production obtained in the reactors enriched with \( CO_2 \) were significantly higher than in the controls. The increase was not linear with the \( CO_2 \) mole fraction of the gas stream used for enrichment, with increase in the cumulative normalised methane production over the controls of 8.0, 5.5 and 13.3% achieved with \( CO_2 \) mole fractions of 0.3, 0.6 and 0.9 respectively.
The observation that the enhancement in renewable energy production is not linear with increasing CO₂ concentrations is in line with the results of (Sat o & Ochi 1994). Sato & Ochi (1994) reported an optimum performance of the AD process applied to waste activated sludge (WAS) treatment when maintaining CO₂ concentrations of 60% volume in the incoming gas stream. In this study a lower performance was obtained for the comparable CO₂ concentration (60% volume) when digesting food waste, with the optimum performance obtained with 90% CO₂ concentration. Thus, both studies confirm that the increase of renewable energy production is not linear with an increasing CO₂ volume concentration, but the obtained optimum CO₂ loads differ. This may be attributable to the difference in the substrate treated, which limits the comparability.

In this project a non optimised operational scenario was tested by saturating the material to digest on one occasion only prior to the digestion process, rather than injecting the CO₂ periodically, which justifies the lower performances obtained when compared with previous studies injecting CO₂ into anaerobic processes (Table 5).

Table 5: Summary of the operational conditions and performances of previous studies enriching anaerobic reactors with CO₂.

<table>
<thead>
<tr>
<th>Digested material</th>
<th>Operational conditions</th>
<th>CO₂ injection</th>
<th>Increase in biogas or methane yield</th>
<th>Increase in methane content of the biogas</th>
<th>CO₂ uptake</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste activated sludge</td>
<td>T=35°C; HRT = 10.8 d; semicontinuous operation of the digesters</td>
<td>Daily CO₂ enrichment with gas mixing line</td>
<td>30% increased specific methane yield (m³ CH₄/kg VS) with CO₂ concentrations of 60% v/v</td>
<td></td>
<td></td>
<td>Sato &amp; Ochi, (1994)</td>
</tr>
<tr>
<td>Mixed primary and secondary sludge</td>
<td>Two-phase AD; T=25°C in first stage and T=42°C in second stage; HRT first stage=8.3 d and HRT second stage=9.0 d</td>
<td>CO₂ enrichment by injection in bottom of the first stage; CO₂ load=0.49 m³/d</td>
<td>25% increased specific methane yield (m³ CH₄/kg VSS) with respect to the full-scale single stage digester used as control</td>
<td>64% methane content vs. 60% of the control</td>
<td>46% of the input*</td>
<td>Salomoni et al., (2011)</td>
</tr>
<tr>
<td>Synthetic solutions; UASB reactor</td>
<td>T=35°C</td>
<td>Dissolved in the influent, which was treated with KOH to maximise the dissolution</td>
<td></td>
<td></td>
<td>69-86%</td>
<td>Alimahmoodi &amp; Mulligan, (2008)</td>
</tr>
</tbody>
</table>

* This value refers to the CO₂ absorbed into the sewage sludge with respect to the amount injected, as opposed to a reduction in the overall digestion emissions itself.

A reduction in the overall CO₂ emissions was obtained in the digesters enriched with CO₂. The reduction increased with higher CO₂ concentrations in the material to digest (higher partial pressures during the initial saturation), but the relationship was not directly proportional since reductions of 3, 10 and 11% where obtained for CO₂ mole fractions during saturation of 0.3, 0.6 and 0.9, respectively. Thus, this project proved the potential of anaerobic processes to act as carbon
sinks when treating food waste previously saturated with CO$_2$. It is envisaged that periodical optimised injections could achieve CO$_2$ uptakes comparable to the 69-86% previously reported by (Alimahmoodi & Mulligan 2008) for UASB reactors, although the difference in the substrate treated limits the comparability.

As far as the digestate quality is concerned, no significant difference in the final pH, TS or VS was observed between control and test reactors. (Sato & Ochi 1994) reported that equal or slightly lower TS and VS reductions were obtained when periodically enriching with CO$_2$ laboratory scale anaerobic digesters (6 L) treating WAS. However, the same study observed some increase in solids reduction when digesting mixed sludge (primary and WAS) in reactors periodically enriched with CO$_2$.

The fact that the pH of the digested material of both control and test reactors were equal implies that any initial pH alteration caused by the CO$_2$ injection was buffered later on during the digestion process. This supports the feasibility of CO$_2$ enrichment by periodic injections, rather than a single initial saturation, if the frequency of injection is adapted to the time required for compensating any possible acidification.

**Conclusions**

1. The potential of the CO$_2$ enrichment technology to improve methane production during food waste digestion was confirmed. Increases of cumulative normalised biogas production and cumulative normalised methane production of 13% were achieved when saturating the food waste before the AD process with a gas stream with $y_{CO2}=0.9$ ($p_{CO2} = 1.6±0.2$ bar).

2. Benefits in terms of CO$_2$ emissions reduction of up to 11% were observed, thus proving the potential of AD processes to act as carbon sinks when treating food waste.

3. There were no significant differences in the digestate produced from the control and test reactors when considering pH, VS and TS.

4. A non optimised operational scenario was tested by saturating the material before the digestion process, being envisaged that periodical optimised injections could achieve significantly higher improvements both in biogas production and carbon emissions.

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**References**

