Optimising biogas production through co-digestion of sewage sludge with food waste and FOG

Olumide Wesley Awe,¹∗ Ranbin Liu,¹ Yaqian Zhao¹,²

¹UCD Dooge Centre for Water Resources Research, School of Civil Engineering, University College Dublin, Newstead, Belfield, Dublin 4, Ireland
²State Key Laboratory of Eco-Hydraulic Engineering in Arid Area, Xi’an University of Technology, Xi’an 710048, P.R. China

ORIGINAL RESEARCH ARTICLE

ABSTRACT

This study focused on the assessment of co-digestion of sewage sludge (SS), food waste (FW) and fat, oil and grease (FOG) to optimise biogas production. A series of batch experiments were conducted under mesophilic conditions with different mixtures of SS, FW, and FOG to optimise the best mixing ratio. The performance of the reactors was assessed based on cumulative methane potential, volatile fatty acid (VFA) effects, ammonium (NH₄⁺-N) effects, soluble chemical oxygen demand (SCOD), volatile solids (VS) and, total solids (TS) removal efficiency. The cumulative methane production of mono-digestion of SS, FW, and FOG is 346, 428 and 898 NmL CH₄/g VS added, respectively, while the mixture of SS, FW, and FOG with a ratio of 70:25:5 (w/w) could achieve the best methane production of 771 NmL CH₄/g VS added.

There was moderate inhibition of VFAs, which could be overcome with a reduction in organic loading rate (OLR) and FW adjustment. NH₄⁺-N was not an inhibition factor in this study. The result also shows a linear increase in methane production and VS reduction in the digestion of the co-mixture of the substrates. Co-digestion can contribute to renewable energy production, diversion of organic waste from landfill and reduction of greenhouse gas (GHG) emissions. Economic and environmental benefits of co-digestion adoption by Ireland wastewater treatment plants (WWTPs) were extensively analyzed and discussed.

KEYWORDS

anaerobic digestion; co-digestion; fat oil; food waste; grease; sewage sludge

1 INTRODUCTION

The anaerobic digestion (AD) process relies on a series of microbial communities and chemical processes that break down biodegradable materials (biomass), such as agriculture residues, organic fraction of solid wastes, sewage sludge (SS) etc., to biogas (methane, carbon dioxide and other trace gases), forming new bacteria cells in the absence of oxygen (Tambone et al., 2010). The complex microbiological degradation has four key biochemical reactions: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. This changes the complex organic materials into a renewable and clean source of energy.

There is an urgent need for the efficient management and disposal of SS and other organic fraction of municipal solid waste (Rizzardi and Goi, 2014). The practical and effective method for degrading and stabilizing these wastes is AD, which converts organic matter into renewable energy. Currently, sewage sludge is mostly digested alone at wastewater treatment plants (WWTPs). The mono-digestion of a single substrate poses problems. For example, sewage sludge has low organic loads. The municipal organic waste contains improper materials and is high in metal content. Animal manure is known to contain a high nitrogen concentration. Wasted oil is high in lipids.
There can be a long chain fatty acid production and inhibitions of methanogenic bacterial communities (Raposo et al., 2011; Wang et al., 2013; Rizzardini and Goi, 2014).

For the AD plant to operate more efficiently, the production of biogas needs to increase, which is possible through anaerobic co-digestion of sewage sludge with other substrates. Anaerobic co-digestion of two or more substrates is better than single substrate digestion, with complementary characteristics. Anaerobic co-digestion shows better kinetic performance and has proven to be a reliable option for increasing biogas yield (Sosnowski et al., 2003; Nielsen and Angelidaki., 2008; Mata-Alvarez et al., 2014; Awe et al., 2017). It is important to select the best co-substrate and blend ratio, to favour synergy, dilute harmful compounds, optimize methane production and maintain digestate quality.

The key for successful anaerobic co-digestion is the substrate, especially its composition and the proportion of each substrate in the feed mixture. It is vital to obtain the best chemical composition in order to optimize the activity of the biomass in the anaerobic process such as carbon-nitrogen ratio, pH, alkalinity etc. (Silvestre et al., 2011; Wang et al., 2015, 2016, 2018). It is also important to avoid the inhibition of different components like ammonia, volatile fatty acids, intermediate products, optimized biogas production and final effluent in the dewatering process (Astals et al., 2014; Xie, et al., (2017). In their contribution to the process stability of anaerobic co-digestion of the AD, Li et al., (2018) canvassed that, process monitoring and control, as well as microbial management, can be used to overcome AD process instabilities and inhibitions. Hagos et al. (2017) argued that anaerobic co-digestion is a reliable alternative option to resolve the disadvantages of single substrate digestion system, which is also related to substrate characteristics and the optimization of the systems.

The objectives of the present study are: 1) to evaluate the optimized mixing carbon to nitrogen (C:N) ratio when SS was co-digested with food waste (FW) and fat, oil and grease (FOG) and assess the volatile solids (VS) removal rate for the purpose of achieving enhanced biogas production with special focus on Irish waste; 2) to assess the economic and environmental benefits of accepting co-digestion of SS with FW and FOG in Ireland. Accordingly, the study investigated the performances of mono-digestion of SS, FW, and FOG. Then, the effects of mixing different proportions (ratios) on bio-methane production were analysed before the optimal mixing ratio was determined.

2. MATERIALS AND METHODS

2.1. Materials

The FW and FOG were collected from various sources.
to secure a nationally representative sample of FW in Ireland (hotel, restaurants, households etc.). The wastes/substrates (FW and FOG) were stored at 4 °C in a refrigerator after removing metals and plastics, large bones and non-biodegradable materials. Prior to use, the waste was ground and homogenized by means of the blender with addition of water for dilution to obtain consistent total solids (TS) content (8-10 % wet weight). Table 1 summarises the characteristics of the FW.

The primary sludge (PS), waste activated sludge (WAS) and inoculum (digested effluent from AD tank) were collected from Ringsend WWTP, Dublin, which is the largest WWTP in Ireland and is operated to provide tertiary treatment for a 1.7 million P.E. The inoculum was incubated at 37 ± 1 °C in water bath. The SS used in this study consisted of thickened waste activated sludge (TWAS) and primary sludge in a 50:50 ratio (on a volumetric basis). Table 1 shows the characteristics of the PS, WAS, and inoculum.

2.2. The batch experimental design and set up

Table 1 shows the AD experimental plan. Monodigestions of SS, FW, and FOG were respectively served as control and various mixing ratios of SS, FW, and FOG was designed in the batch tests marked as R5-R13 in Table 1. The experimental set-up, as shown in Figure 1, consists of three separate but linked units, forming a whole. The first unit consists of a temperature-controlled water-bath with 26 reactors bottles of 250 mL volume and air-tight sealed in two sets. Each bottle was flushed with pure Nitrogen for three minutes to create anaerobic conditions. All the bottles were incubated in the water-bath under mesophilic (37 ± 1 °C) conditions. The second part consists of 26 carbon dioxide (CO₂) removal units using 3 N sodium hydroxide (an alkaline solution) that absorbs the CO₂ and hydrogen sulphide (H₂S), in biogas production. The third unit consists of 26 gas collection and measuring devices called Tedlar® Gas Sampling Bags, couple with screw cap valve (SCV) connected to the CO₂ removal units. The accumulated methane volume was measured with a graduated 100 mL gas-tight glass syringe (Fortuna, Germany), normalized (0 °C, 1 atm, and dry gas) and calculated. The AD process was stopped after 20 days when the volume of gas production was lower than 2 mL/bottle per day.

The anaerobic reactors used were 250 mL serum bottles with working volume of 200 mL for the cumulative methane potential (CMP) test, which contained well-adapted seed inoculum, with 50 mL headspace for gas collection (Wang et al., 2013). The inoculum to substrate (I/S) ratio used was 2:1 on VS content of 1.72 % (w/w) and pH of 7.4. This ratio (2:1) is an important parameter in the AD process and has been recommended by many researchers (Raposo et al., 2011). All samples (R2-R13) are tested in duplicates and in two separate sets, making a total of 26 samples. As shown in Table 1, the blank test was conducted on the inoculum in duplicate (R1), and the net methane yield from the blank was subtracted from the samples.

<table>
<thead>
<tr>
<th>Reactors</th>
<th>Co-digestion substrates</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>Inoculum (blank)</td>
</tr>
<tr>
<td>R2</td>
<td>Inoculum + (SS) - 100:0</td>
</tr>
<tr>
<td>R3</td>
<td>Inoculum + (FW) - 100:0</td>
</tr>
<tr>
<td>R4</td>
<td>Inoculum + (FOG) - 100:0</td>
</tr>
<tr>
<td>R5</td>
<td>Inoculum + (SS + FW) - (80:20)</td>
</tr>
<tr>
<td>R6</td>
<td>Inoculum + (SS + FW) - (60:40)</td>
</tr>
<tr>
<td>R7</td>
<td>Inoculum + (SS + FW) - (40:60)</td>
</tr>
<tr>
<td>R8</td>
<td>Inoculum + (SS + FW) - (20:80)</td>
</tr>
<tr>
<td>R9</td>
<td>Inoculum + (SS + FOG) - (90:10)</td>
</tr>
<tr>
<td>R10</td>
<td>Inoculum + (SS + FW + FOG) - (70:25:5)</td>
</tr>
<tr>
<td>R11</td>
<td>Inoculum + (SS + FW + FOG) - (60:35:5)</td>
</tr>
<tr>
<td>R12</td>
<td>Inoculum + (SS + FW + FOG) - (50:45:5)</td>
</tr>
<tr>
<td>R13</td>
<td>Inoculum + (SS + FW + FOG) - (45:50:5)</td>
</tr>
</tbody>
</table>

SS (50:50) mixtures of primary and waste activated sludge
(R2-R13) mixed with inoculum to assess the cumulative methane production (CMP) yields from the samples only. The reactors were shaken by hand twice daily to avoid mass transfer limitations and the volume of methane was measured.

A smaller percentage (5% v/v) of oil was added based on the experience of previous studies of accumulation of long chain fatty acids (LCFA) and high concentration of VFAs during AD process (Long et al., 2012; Cho et al., 2013; Awe et al., 2017). The experiment ran for 20 days, and the residual digestate was analysed after AD for pH, VS (conversion efficiency %), TS (removal efficiency %), tVFAs (total volatile fatty acids), alkalinity or TIC (total inorganic carbon), NH$_4^+$-N, SCOD (soluble chemical oxygen demand), TOC (the total organic carbon), as well as daily methane yields. Finally, the specific methane potential (SMP) (mL CH$_4$ gVS$^{-1}$) test was conducted to measure the methane production and compositions from the co-digestion of the various substrate mixes. The characteristics of the FW, FOG, PS, WAS and inoculum are jointly shown in Table 2.

### Table 2. Characterisation of substrates used for anaerobic co-digestion and cumulative methane production of substrates

<table>
<thead>
<tr>
<th>Parameters</th>
<th>R1</th>
<th>R2</th>
<th>R3</th>
<th>R4</th>
<th>R5</th>
<th>R6</th>
<th>R7</th>
<th>R8</th>
<th>R9</th>
<th>R10</th>
<th>R11</th>
<th>R12</th>
<th>R13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inoc.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inoc.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TS (%)</td>
<td>2.17</td>
<td>2.35</td>
<td>7.27</td>
<td>93.65</td>
<td>3.06</td>
<td>4.14</td>
<td>4.94</td>
<td>5.57</td>
<td>5.67</td>
<td>4.85</td>
<td>4.39</td>
<td>5.62</td>
<td></td>
</tr>
<tr>
<td>VS (%)</td>
<td>1.72</td>
<td>1.64</td>
<td>6.77</td>
<td>nd</td>
<td>2.60</td>
<td>3.65</td>
<td>4.42</td>
<td>5.04</td>
<td>4.52</td>
<td>4.26</td>
<td>3.96</td>
<td>5.06</td>
<td></td>
</tr>
<tr>
<td>VS/TS (%)</td>
<td>79.27</td>
<td>69.72</td>
<td>93.13</td>
<td>nd</td>
<td>84.77</td>
<td>88.17</td>
<td>89.48</td>
<td>90.71</td>
<td>90.96</td>
<td>87.65</td>
<td>90.10</td>
<td>90.14</td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>7.4</td>
<td>7.3</td>
<td>7.1</td>
<td>8.2</td>
<td>7.2</td>
<td>7.3</td>
<td>7.3</td>
<td>7.4</td>
<td>8.4</td>
<td>7.9</td>
<td>7.8</td>
<td>7.8</td>
<td></td>
</tr>
<tr>
<td>NH$_4^+$ (mg/L)</td>
<td>300</td>
<td>236</td>
<td>194</td>
<td>1215</td>
<td>251</td>
<td>210</td>
<td>218</td>
<td>230</td>
<td>1473</td>
<td>1473</td>
<td>1566</td>
<td>1601</td>
<td></td>
</tr>
<tr>
<td>TOC (mg/L)</td>
<td>2709</td>
<td>2917</td>
<td>5028</td>
<td>1006</td>
<td>3108</td>
<td>3873</td>
<td>4899</td>
<td>4857</td>
<td>3207</td>
<td>3567</td>
<td>4671</td>
<td>4710</td>
<td></td>
</tr>
<tr>
<td>SCOD (mg/L)</td>
<td>9840</td>
<td>8760</td>
<td>23220</td>
<td>50800</td>
<td>13380</td>
<td>18180</td>
<td>23400</td>
<td>23580</td>
<td>4750</td>
<td>50250</td>
<td>57000</td>
<td>63500</td>
<td></td>
</tr>
<tr>
<td>TN (mg/L)</td>
<td>1908</td>
<td>1629</td>
<td>1419</td>
<td>nd</td>
<td>1671</td>
<td>1755</td>
<td>1635</td>
<td>1527</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>C/N</td>
<td>5.16</td>
<td>5.38</td>
<td>16.36</td>
<td>nd</td>
<td>8.01</td>
<td>10.36</td>
<td>14.31</td>
<td>15.44</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td></td>
</tr>
<tr>
<td>TA (mgCaCO$_3$/L)</td>
<td>3120</td>
<td>2640</td>
<td>1800</td>
<td>1640</td>
<td>2160</td>
<td>2440</td>
<td>1560</td>
<td>1360</td>
<td>2280</td>
<td>2520</td>
<td>2160</td>
<td>2200</td>
<td></td>
</tr>
<tr>
<td>tVFA (mg/L)</td>
<td>98.4</td>
<td>762.4</td>
<td>629.6</td>
<td>98.4</td>
<td>1160</td>
<td>762.4</td>
<td>1028</td>
<td>1692</td>
<td>364.0</td>
<td>762.4</td>
<td>496.8</td>
<td>496.8</td>
<td></td>
</tr>
<tr>
<td>VFA/TIC</td>
<td>0.03</td>
<td>0.29</td>
<td>0.35</td>
<td>0.06</td>
<td>0.51</td>
<td>0.31</td>
<td>0.66</td>
<td>1.24</td>
<td>0.16</td>
<td>0.30</td>
<td>0.23</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>CMP (NmL CH$<em>4$/g VS$</em>{added}$)</td>
<td>274</td>
<td>346</td>
<td>428</td>
<td>898</td>
<td>526</td>
<td>476</td>
<td>546</td>
<td>569</td>
<td>486</td>
<td>771</td>
<td>392</td>
<td>694</td>
<td></td>
</tr>
</tbody>
</table>

*nd: not done


The research investigated the possibility of FW and FOG co-digestion with SS to enhance biogas production. As waste characterization and analysis is one of the most important steps in the AD process, the general composition of the input materials (substrates) to the system is essential for estimating the amount and composition of the biogas produced as well as the amount of energy contained in the biogas. As expected, FW and FOG are rich in carbon content and organics, and therefore had higher VS/TS ratio of 93.1%, 99.0%, respectively, as compared to sewage sludge with VS/TS of 69.7%. The nitrogen content of sewage sludge is much higher than for FW, which resulted in a smaller C/N ratio of SS (5.38), whereas the C/N ratio of FW in this study was 16.36. The values of TS and VS obtained from FW and FOG are much higher than for SS. Consequently, as the VS of FW increases in the mixtures, the values of VS/TS also increase. For example, the value VS/TS for SS alone was (69.72%) but increased when mixed with FW: 84.77% (80:20), 88.17% (60:40), 89.48% (40:60), and up to 90.71% when the SS: FW mixtures reach 20:80 (Table 1). This also corresponded with the increasing C/N ratios of 8.01 (80:20), 10.36 (60:40), 14.31 (40:60), and up to 15.44 at 20:80 SS: FW mixing ratio. This adjustment of C/N ratio resulted in higher methane production than was produced through SS mono-digestion.

### 3.1. Effect of co-digestion on methane production and rates

The research investigated the possibility of FW and FOG co-digestion with SS to enhance biogas production. As waste characterization and analysis is one of the most important steps in the AD process, the general composition of the input materials (substrates) to the system is essential for estimating the amount and composition of the biogas produced as well as the amount of energy contained in the biogas. As expected, FW and FOG are rich in carbon content and organics, and therefore had higher VS/TS ratio of 93.1%, 99.0%, respectively, as compared to sewage sludge with VS/TS of 69.7%. The nitrogen content of sewage sludge is much higher than for FW, which resulted in a smaller C/N ratio of SS (5.38), whereas the C/N ratio of FW in this study was 16.36. The values of TS and VS obtained from FW and FOG are much higher than for SS. Consequently, as the VS of FW increases in the mixtures, the values of VS/TS also increase. For example, the value VS/TS for SS alone was (69.72%) but increased when mixed with FW: 84.77% (80:20), 88.17% (60:40), 89.48% (40:60), and up to 90.71% when the SS: FW mixtures reach 20:80 (Table 1). This also corresponded with the increasing C/N ratios of 8.01 (80:20), 10.36 (60:40), 14.31 (40:60), and up to 15.44 at 20:80 SS: FW mixing ratio. This adjustment of C/N ratio resulted in higher methane production than was produced through SS mono-digestion.

#### 3.1.1. Effects on daily methane production on all substrates

Figure 2 shows the daily methane production from mono-digestion and co-digestion of SS with FW and FOG. The highest daily methane production rate came from reactors R10 (75:25:5) with 444 NmL CH₄/g VS added followed by R12 (50:45:5), R8 (20:80) and R13 (45:50) with 319 NmL CH₄/g VS added, 243 NmL CH₄/g VS added, and, 220 NmL CH₄/g VS added respectively, in the first 24 h. These peaks including that of FW alone could be caused by the high concentration of carbohydrates in the mixtures, which were biodegraded rapidly and have a higher conversion rate than proteins and lipids (Kafle et al., 2012). The highest daily methane production for mono-digestion of SS (R2), FW (R3) and FOG (R4) is 59, 130, and 10 NmL CH₄/g VS added, respectively in the first 24 h. The low-gas production in the first few days of reactor R4 might be lag-phase which could indicate a hydrolysis limitation of lipids to anaerobic bacteria in the start-up phase (Davidsson et al., 2008). Lipids degradation is seen as a rate-limiting step for FW anaerobic digestion. The reactor R4 reached its maximum daily production on day 11, 12 and, 13, with 100, 130, and 100 NmL CH₄/g VS added, respectively, indicating recovery and adaptation of the bacteria. The second peak (from day 5 to day 15) may be attributed to the subsequent degradation of proteins and lipids in the mixtures, especially R4 (FOG). The methane production rates declined sharply after 48 hours for all the substrates, especially FW, which might be owing to acidification and production of VFA together with FW.
With the co-digestion mixtures, no lag-phase or delay in gas production was noticed and methane production started immediately as shown in Figures 3 and 4. However, the peak values of daily methane production for mixture R9 (58) were less than those of R2 and R3. This may be because there was higher oil addition (10%) as against 5% added to the other mixes. The higher oil addition probably causes a lag-phase owing to hydrolysis limitation of lipids until the bacteria acclimatize to the high organic loading rate in the mixtures. The peak values of daily methane production for mixtures R10, R12, and R13 were 86.71%, 81.51%, and 73.18% higher than those for a single substrate SS (R2), and 70.72%, 59.25% and, 40.91% higher than (R3) FW alone.

The mixture R11 daily peak methane production was far less than that of R2 and R3, which might be caused by initial lag-phase which later recovered after biomass acclimatization and biogas resumed production normally. The methane production peak occurs in the first 6 days, followed by a sharp decline in production with R10 down to 7 NmL CH$_4$/g VS$_{added}$, 32 NmL CH$_4$/g VS$_{added}$, and 3 NmL CH$_4$/g VS$_{added}$ in days 6, 7 and 8. In contrast, R10, R12, and R13 continued steady methane production, probably owing to the adaptation of the bacteria community, until day 17 when production declined and finally stopped.

3.1.2. Effects on cumulative methane productions on all substrates
The AD batch experiments were conducted to compare the methane production potential of SS, FW, and FOG in mono-digestion with co-digestion of the substrates. Figure 3(a) shows the cumulative methane production of mono-digestion (SS, FW, and FOG); R2, R3, and R4 are respectively shown in Figure 3a. The methane production is 346, 428 and 898 NmL CH$_4$/g VS$_{added}$ for R2, R3, and R4, respectively. The C/N ratio for R3 was 5.38 and for R5 it was 16.36.

Different proportions of the substrate were mixed (Table 1) to evaluate the methane production and investigate the effect of FW co-digestion with SS. Figure 3b shows the cumulative methane production for the co-digested substrates. The methane production for R8 started immediately, rose to 243 NmL CH$_4$/g VS$_{added}$ within 24 hours and declined sharply to 94 NmL CH$_4$/g VS$_{added}$ 48 hours later, with a cumulative value of 569 NmL CH$_4$/g VS$_{added}$. This shows 64.45% (1.64 times) more than digesting of R2 (SS) alone and 32.94% (1.33 times) higher than digesting R3 (FW)

![Figure 2. Daily methane production rate from mono-digestion and co-digestion of substrates (SS, FW, and FOG), with different mixing ratios](image-url)
waste alone with C/N ratio 15.44. As compared with mono-digestion curves, there is a short-lag phase in methane production of the mixtures, which is likely caused by quick adaptation to the new substrates (Switzenbaum et al., 1990). It was also noted that the methane production was proportional to the content of food waste in the substrates. The methane production levels for R5, R6, and R7 were 526, 476 and 546 NmL CH₄/g VS added which corresponds to 50.02% (1.52 times), 37.57% (1.38) and 57.8% (1.58 times), respectively, than SS digestion alone.

Figure 3. Cumulative methane production from; (a) mono-digestion of substrates (SS, FW & FOG) as control; (b) co-digestion of substrates (SS and FW) with different mixing ratios without FOG addition.FW, and FOG), with different mixing ratios

Furthermore, about 5% w/w of kitchen wasted oil was added to different mixtures of SS and FW (R9-R13) as shown in Table 2, to investigate the biomethane potential of such mixtures. Figure 4a and 4b present the cumulative methane production of the mixtures. Methane production started immediately profusely for R10 (444 NmL CH₄/g VS added), R12 (319 NmL CH₄/g VS added) and R13 (220 NmL CH₄/g VS added), but R9 (58 NmL CH₄/g VS added) and R11 (38 NmL CH₄/g VS added) started rather slowly after 24 hours. The cumulative methane production levels for mixtures R9 and R10 were 40.46% (1.4 times) and 122.83% (2.23 times) higher than that of single substrate SS (R2), and 13.55% (1.14 times) and 80.14% (1.8 times) higher than (R3) FW alone. As for the mixtures R11, R12 and R13, their cumulative values were 13.29% (1.13 times), 100.58% (2.01 times) and 109.54% (2.1 times) higher than SS and, -8.41% (0.9 times lesser), 62.15% (1.62 times) and 69.39% (1.69 times) for FW.

Figure 4. Cumulative methane production from; (a) co-digestion of substrates (SS, FW) with 5% FOG addition; (b) combination of mono-digestion and co-digestion of substrates with different mixing ratios with and without oil additions

3.2. Effect of co-digestion on biochemical parameters

3.2.1. TS reduction and VS conversion efficiencies of the substrates

The effects of anaerobic co-digestion of SS with FW and FOG on anaerobic biodegradability were evaluated in terms of the organic removal efficiency and biochemical parameters or conversion efficiency. The TS and VS reduction efficiencies of all mono-substrates and co-substrates before and after digestion were determined with Eq. (4) and are presented in Figure 5a and 5b. This is one of the most useful parameters for evaluating the
efficiency of the AD, through a reduction in volatile solids and total solids after analysing the digestate. Figure 5a shows that the TS removal efficiencies of the reactors were in the range of 8-46%. The highest rate of TS removal of 46% was achieved at reactor R13 including the mixture of SS: FW: FOG (45:50:5). The lowest removal efficiency of 8% was obtained in reactor R11 that contained mixture(60:35:5). The same trend persistent with VS destruction rate of 10% of reactor R11. This also explained the lowest methane production from the reactor R11, out of all the co-digested substrates with the production of merely 392 NmL CH\textsubscript{4}/g VS\textsubscript{added}. The results showed that addition of FW and FOG into the reactors as co-substrate with SS increased the TS removal efficiencies by 54% and 67% higher than mono-digestion of SS and FW, respectively.

Table 3. Characterisation of digestate recovered after digestion

<table>
<thead>
<tr>
<th>Reactors</th>
<th>Co-digestion substrates</th>
<th>Initial TS (%)</th>
<th>Final TS (%)</th>
<th>Initial VS (%)</th>
<th>Final VS (%)</th>
<th>Initial SCOD (mg/l)</th>
<th>Final SCOD (mg/l)</th>
<th>Initial TOC (mg/l)</th>
<th>Final TOC (mg/l)</th>
<th>Initial pH</th>
<th>Final pH</th>
<th>Final TA (mgCa\textsubscript{CO}\textsubscript{3}/L)</th>
<th>Final tVFA (mg/l)</th>
<th>VFA/TIC</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>Inoculum</td>
<td>2.17</td>
<td>2.03</td>
<td>1.72</td>
<td>1.54</td>
<td>9840</td>
<td>2709</td>
<td>1970</td>
<td>7.4</td>
<td>8.1</td>
<td>3000</td>
<td>-167</td>
<td>0.06</td>
<td></td>
</tr>
<tr>
<td>R2</td>
<td>Inoculum + (SS – 100:0)</td>
<td>2.35</td>
<td>1.86</td>
<td>1.64</td>
<td>1.32</td>
<td>8760</td>
<td>2917</td>
<td>2078</td>
<td>7.2</td>
<td>8.2</td>
<td>2840</td>
<td>98.4</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>R3</td>
<td>Inoculum + (FW) – 100:0</td>
<td>7.27</td>
<td>6.27</td>
<td>6.77</td>
<td>3.94</td>
<td>23220</td>
<td>5028</td>
<td>13818</td>
<td>7.0</td>
<td>13.3</td>
<td>7600</td>
<td>3816</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>R4</td>
<td>Inoculum + (FOG) – 100:0</td>
<td>93.65</td>
<td>88.55</td>
<td>254000</td>
<td>127500</td>
<td>2006</td>
<td>9220</td>
<td>8.2</td>
<td>5.6</td>
<td>5280</td>
<td>5012</td>
<td>0.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>R5</td>
<td>Inoculum + (SS + FW) – (80:20)</td>
<td>3.06</td>
<td>2.68</td>
<td>2.60</td>
<td>1.96</td>
<td>13380</td>
<td>3108</td>
<td>2179</td>
<td>7.2</td>
<td>8.4</td>
<td>3320</td>
<td>-34.4</td>
<td>-0.01</td>
<td></td>
</tr>
<tr>
<td>R6</td>
<td>Inoculum + (SS + FW) – (60:40)</td>
<td>4.14</td>
<td>2.98</td>
<td>3.65</td>
<td>2.42</td>
<td>18180</td>
<td>3873</td>
<td>8400</td>
<td>7.3</td>
<td>6.5</td>
<td>2200</td>
<td>3020</td>
<td>1.37</td>
<td></td>
</tr>
<tr>
<td>R7</td>
<td>Inoculum + (SS + FW) – (40:60)</td>
<td>4.94</td>
<td>3.06</td>
<td>4.42</td>
<td>2.57</td>
<td>23400</td>
<td>4899</td>
<td>9135</td>
<td>7.3</td>
<td>6.1</td>
<td>2240</td>
<td>3153</td>
<td>1.41</td>
<td></td>
</tr>
<tr>
<td>R8</td>
<td>Inoculum + (SS + FW) – (20:80)</td>
<td>5.57</td>
<td>4.04</td>
<td>5.05</td>
<td>3.30</td>
<td>23580</td>
<td>4857</td>
<td>10707</td>
<td>7.4</td>
<td>6.0</td>
<td>2200</td>
<td>3418</td>
<td>1.55</td>
<td></td>
</tr>
<tr>
<td>R9</td>
<td>Inoculum + (SS + FOG) – (90:10)</td>
<td>4.39</td>
<td>3.56</td>
<td>3.96</td>
<td>3.25</td>
<td>41750</td>
<td>76750</td>
<td>3207</td>
<td>6165</td>
<td>8.4</td>
<td>7.0</td>
<td>2760</td>
<td>2223</td>
<td>0.81</td>
</tr>
<tr>
<td>R10</td>
<td>Inoculum + (SS + FW + FOG) – (70:25:5)</td>
<td>5.15</td>
<td>4.1</td>
<td>4.52</td>
<td>3.42</td>
<td>50250</td>
<td>106500</td>
<td>3567</td>
<td>8850</td>
<td>7.9</td>
<td>6.5</td>
<td>2360</td>
<td>3153</td>
<td>1.34</td>
</tr>
<tr>
<td>R11</td>
<td>Inoculum + (SS + FW + FOG) – (60:35:5)</td>
<td>4.85</td>
<td>4.47</td>
<td>4.26</td>
<td>3.85</td>
<td>57000</td>
<td>113250</td>
<td>4671</td>
<td>8415</td>
<td>7.8</td>
<td>6.2</td>
<td>2000</td>
<td>3817</td>
<td>1.91</td>
</tr>
<tr>
<td>R12</td>
<td>Inoculum + (SS + FW + FOG) – (50:45:5)</td>
<td>5.07</td>
<td>3.43</td>
<td>5.04</td>
<td>2.91</td>
<td>63500</td>
<td>155750</td>
<td>4614</td>
<td>9070</td>
<td>7.8</td>
<td>6.1</td>
<td>2280</td>
<td>4082</td>
<td>1.79</td>
</tr>
<tr>
<td>R13</td>
<td>Inoculum + (SS + FW + FOG) – (45:50:5)</td>
<td>5.62</td>
<td>3.09</td>
<td>5.06</td>
<td>2.67</td>
<td>71750</td>
<td>170750</td>
<td>4710</td>
<td>9475</td>
<td>7.8</td>
<td>6.2</td>
<td>2000</td>
<td>3684</td>
<td>1.84</td>
</tr>
</tbody>
</table>

SS : (50:50) mixtures of primary and waste activated sludge
From Figure 5b, the VS removal efficiencies of mono-digestions of SS (R2) and FW (R3) were 20% and 44%, respectively. The highest VS removal efficiency of 49% was achieved in the reactor R13 having the mixture of SS: FW: FOG (45:50:5). The lowest removal efficiency of 10% was obtained in reactor R11 (60:35:5). This was a similar trend with TS removal as well. The results showed that the addition of FW and FOG into the reactors as co-substrate with SS increased the VS conversion efficiencies by 59.2% and 10.21% higher than mono-digestion of SS and FW respectively, by reactor R13. Reactor R3 containing FW performed better than a few mixed substrates reactors, in term of VS conversion efficiency owing to the readily biodegradable nature of FW, with reactors R8 (36%), R10 (35%) and R11 with merely 10%. Reactor R8, for example, contained (20:80), 80% of FW and R11 contained 35% of FW, and these characteristics have an effect on the methane production from the substrates. Besides, R9 which contained mixtures of SS: FOG (90:10), with 90% SS and 10% w/w of FOG, achieved VS conversion efficiency of 25% higher the SS (R2) mono-digestion. The reported values by other researchers were found slightly different with the findings of this study (Davidsson et al., 2008; Luste and Luostarinen, 2010; Meng et al., 2015), which made the findings more significant.

3.2.2. Effects on VFAs, VFA/TIC, \(\text{NH}_4^+\)-N and PH
As shown in Figure 6, the accumulated compounds in this study for co-digestion of SS with FW and FOG were found to include tVFAs, which are suspected to be responsible for the decrease in pH values of reactors, especially those that contained three mixtures of SS: FW: FOG.

These VFAs result from the degradation of polysaccharide, protein, and lipid, which normally increased at the beginning stage leading to pH reduction. The values of tVFAs and TA were 3,816 mg/L and 7,600 mgCaCO\(_3\)/L, respectively, with VFA/TIC of 0.5. The VFA increase in reactors ranges from R10 (2520 mg/L-3152.8 mg/L), R11 (2160 mg/L-3816.8 mg/L), R12 (2200 mg/L-4082.4 mg/L) and 2440 mg/L-3684 mg/L). This corresponds to increases of 25.08%, 76.7%, 46.11% and 85.56% for R10, R11, R12, and R13 respectively. This explained the rise in VFA/TIC values as shown.

This rise in VFAs was caused by the rapid accumulation of VFAs during hydrolysis, owing to the higher growth rate of acidogens as compared to methanogens during the process as reported by (Hill and Holmberg, 1988). It is understood that the acid-consumping methanogenic archaea are extremely sensitive and are more inhibited by an acid accumulation and decreasing pH than the acid-producing species (Anderson and Yang, 1992; Koch et al., 2016). Lastly, VFA concentration in the range of 1000-3000 mg/L would cause moderate inhibition (Duan et al., 2012). In the present study, VFAs concentrations were in the range of 98.4-5012 mg/L, as shown in Table 3. The lower pH also affected lower values of alkalinity which contributed to low methane production at the end of the experiment by reactors (R10-R13).

Figure 5. Reactor performance of substrates with different mixing ratios; (a) TS content and reduction efficiency of the reactors; (b) VS content and conversion efficiency of the reactors.

Alkalinity is the capacity of the digester to neutralize acids; the ratio of VFA/TIC is used as a measurement to evaluate anaerobic system stability. The ratio between 0.2-0.6 implied stable process without the risk of acidification (Lossie and Pütz, 2008). And in this study, \(\text{NH}_4^+\)-N concentration fell in the range of 194 - 1,668 mg/L for all reactors R1-R13 before, and 1917 - 2,294 mg/L for reactors R9-R13 after digestion. This is lower than the tolerable or critical \(\text{NH}_4^+\)-N concentration for methanogenic microorganisms to stop growing or react negatively is...
3,000 mg/L. It is interesting to find that the NH\textsubscript{4}\textsuperscript+-N before digestion was 1,215 mg/L and increased to just 1,338 mg/L for R4, which amounts to an increase of just 10.12%.

4. DISCUSSION

4.1. Benefits of co-digestion in this study

The values CMP in this study are close to the theoretical CH\textsubscript{4} potential of carbohydrate, protein, and lipid (88.56%) as reported by (Angelidaki and Sanders, 2004), which were 415, 496, and 1014 NmL CH\textsubscript{4}/g VS\textsubscript{added}, calculated using (Buswell and Neave, 1930) formula. The results are slightly different with Luostarinen et al., (2009) findings of methane production potential of SS (263 m3CH\textsubscript{4}/t VS\textsubscript{added}), and grease trap sludge (918 m3CH\textsubscript{4}/t VS\textsubscript{added}). (Davidsson et al., 2008) reported methane potential batch result of 325 NmL/g VS\textsubscript{in} for SS and (845-928 NmL/g VS\textsubscript{in}) for grease trap sludge, which agrees with the present study. Similarly, Koch et al., (2015) found SS and FW potentials of 330 LCH\textsubscript{4}/kg VS and 450 LCH\textsubscript{4}/kg VS, respectively. Some other researchers found different results, such as Meng et al., (2015), who found FW potential of 697.4 mL/g VS, while Xie et al., (2017) reported 159 mL/g VS\textsubscript{added} for primary sludge and 652 mL/g VS\textsubscript{added}. The reason for these large differences is due to high lipid contents of Chinese FW which amount to 22.8-31.45% (Chen et al., 2010; Zhang et al., 2013; Meng et al., 2015). Interestingly, Meng et al., (2015) result for oil (fat) of 899.8 mL/g VS\textsubscript{in} is in close agreement with this study. Dennehly et al., (2016), who co-digest food waste with pig manure reported a biomethane potential of 370 NmL CH\textsubscript{4}/g VS, which was lower than the result in the present study.

The complementary benefits of FW/SS co-digestion lie in the ability of SS to provide adequate micro and macronutrients, moisture content and alkalinity, but low in C/N ratio and methane production, which are in balance with FW, that is characterized by high solid concentration and high C/N ratio. This study revealed that the C/N ratios increased with the addition of FW to the mixes to balance and dilute the inhibitory compounds in the SS with C/N ratio of R5 (8.01), R6 (10.36), R7 (14.31) and R8 (15.44). This resulted in higher methane production than was produced through SS mono-digestion. Additionally, co-digestion of SS/FW provides nutrients, improving the biodegradability

Figure 6. The dynamic changes of (a) alkalinity (TIC) and tVFA of the 13-reactor’s combined, before and after digestion, (b) effect of reactors’ final pH on tVFA after digestion, (c) effect of the reactors’ final pH on TA after digestion and, (d) Effect of pH on VS conversion efficiency with different mixtures in the process of AD under mesophilic condition
of the substrates. About 90% of the total methane produced with all the reactors is produced in the first 15 days (Figures 3 and 4). It is evident that the addition of these co-substrates showed an increase in biomass activities, especially when using with FW as co-substrate. Also, the addition of used oil (rich in lipids) promoted the LCFAs β-oxidation process of the syntrophic acetogenic oxidising microorganisms in aiding methane production. The gradual addition of FOG dose to the AD is a good strategy to enhance fat degradation, thereby reducing LCFAs inhibition effects on the process.

Another significant advantage of co-digestion is to regulate the VFA/TIC ratio in the reactor. It has been shown by (Raposo et al., 2011) that, a drop in pH, leads to an increase in VFA/TIC ratio (>0.4), because of high VFA concentrations. Thus, the failure of the reactors (R6-R13) agrees with (Borja et al., 2004; Lossie and Pütz, 2008) findings that the operation of the AD will cease to be stable at a higher FOS/TAC ratio above >0.5. On the other hand, the buffering capacity (alkalinity) of the reactors reduced significantly for R10, from the initial 2520 mg CaCO₃/L when oil was added to 2360 mg CaCO₃/L, a reduction of 6.35%, while that of R13, reduced from the initial 2440 mg/L CaCO₃ when oil was added to 2000 mgCaCO₃/L, a reduction of 22% as shown Figure 6c. But, the alkalinity values for mono-digestion reactors R2, R3, R4 increased from 2640-2840 (7.58%), 1800-7600 (322.22%) and 1640-5280 (221.95%) (mg CaCO₃/L) respectively, which leads to lower VFA/TIC values as presented. The tolerable or critical ammonium concentration for methanogenic microorganisms to stop growing or react negatively is 3,000 mg/L.

Many researchers have suggested that ammonia can also buffer or neutralise the VFAs during the anaerobic digestion process, thereby stabilising the system and avoiding AD failure (Banks et al., 2011; Wang et al., 2015; Zhang et al., 2017). The result of this study is not in agreement with the findings of Banks et al., (2012), who reported a higher ammonia concentration of more than 5,000 mg/L, during AD of FW. Surprisingly, NH₄⁻N has been relatively stable even after the addition of 5% oil contents to the reactors which is positive for this study. And in this study, NH₄⁻N concentration fell in the range of 194 - 1,668 mg/L for all reactors R1-R13 before and 1917 - 2,294 mg/L for reactors R9-R13 after digestion, which is lower than the critical NH₄⁻N concentration of 3,000 mg/L. Nevertheless, the methane production continued to reduce significantly towards the end of the experiments for all the reactors.

This is therefore significant for this study because, the reported inhibition effects such as LCFAs accumulation, sludge floatation, and lag-phase during hydrolysis stage should not prevent the exploitation of utilizing lipid wastes in an AD for methane production. The results obtained from this study showed an increase in methane production under different mixing ratios of the three substrates. It is important to assess the benefits of the results and their potential implementation in the existing anaerobic digestion systems at WWTPs, especially WWTPs in Ireland.

4.2. Lessons for the waste management in Ireland

In Ireland, there is at present very little co-digestion of FW with SS. Some farm-based plants co-digest animal manure with municipal solid wastes, energy crops and glycerin from biodiesel plants. There are only three small-scale anaerobic digestion facilities in Ireland, McDonnel Farm Biogas Limited, Ballyshannon Recycling Limited and Bio-Energy and Organic Fertilizer (BEOFS). At present, WWTPs in Ireland do not accept FW and FOG and their excess capacity is underused; except for a few like Ringsend WWTP, Shanganagh WWTP and Sligo WWTP which serve as sludge treatment hubs that anaerobically digest their produced sludge. Most of the sludge produced from the other 167 plants is sent to landfill. FOG being generated in Ireland cannot alone be digested, because it will lead to process instability through LCFA inhibition, too wet for efficient composting and so unsuitable for the landfill as reported (Davidsson et al., 2008; Luostarinen et al., 2009). Ireland generates over 1 million tonnes of FW annually (from the MSW) and this includes; households, commercial firms, and food producers.

Ringsend WWTP provides up to tertiary treatment for a 1.7 million population equivalent (P.E.). Its sewage sludge is treated using the Cambi Thermal Hydrolysis Process (THP) and anaerobic digestion (AD) before being thermally dried. The installed capacity of the plant is 120,000 tDS/yr of sewage sludge, with biogas yield of an average of 410 m3/tDS. Currently, the anaerobic digestion produces 45,000 m³/day of biogas (Awe et al., 2016). This is used to fuel boilers and to generate electricity and recover heat through the Combined Heat and Power (CHP) system, which can generate more than 2 Mega Watts (MW) of electricity, for 50% of the heat and electricity required at the plant. This is enough to provide electrical energy to power up to 6,000 domestic homes. The CHP system also
generates electricity from natural gas for the plant's total energy demand. A total of 4 MW of capacity is installed at Ringsend (Awe et al., 2016; Celtic Anglian Water, 2016). The plant does not at present accept any organic waste for co-digestion.

The plant's energy production will increase, if the 30% unused capacity is to be used for co-digestion of FW and FOG with SS. This can be achieved by using the result of reactor R10 (70:25:5) with methane production of 771 NmL CH\textsubscript{4}/g VS\textsubscript{added} about 123% (2.23 times) higher than SS mono-digestion. This is 30% of feed VS and, interestingly, the sewage sludge and the inoculum used for this study were collected from Ringsend WWTP. Their biogas production would increase to 100,350 m\textsuperscript{3}/day of biogas according to the results obtained. This could translate into 36.6 million m\textsuperscript{3} of pure methane per year with an energy yield of 386,422,762 kWh (386.42 GWh/year), assuming 10.55 kWh equals 1 m\textsuperscript{3} CH\textsubscript{4} and 35% energy conversion efficiency of the generators. The suggested mixing ratios used in this study could also be adjusted to obtain more methane production for alternative energy purposes.

Other options would be to invest in new gas engines, such as GE gas turbine with higher conversion efficiency; or if the gas turbine is made to operate in combined cycle mode, using the exhaust to produce steam to drive a steam turbine. This is because efficiencies of more than 55% and close to 60% are now being achieved for the entire cycle. For example, General Electric (GE) launched an HA Heavy-duty Gas Turbine that broke the power plant efficiency records by at 62.22% efficient rating for a combined-cycle power plant, at Bouchain power plant, France with the capacity to generate over 650 MW, which is enough to power 680,000 homes (Electric, 2017).

4.3. Future research suggestions

Further research using continuous stirred-tank reactors (CSTRs) under mesophilic conditions is needed to investigate in detail the economic feasibility as predicted from the results and discussions in this study. This will validate the predicted energy production from Ringsend WWTP as suggested. This strategy will not only provide renewable energy but also reduce the cost of municipal waste management, by diverting waste from landfill, ensuring a cleaner environment and reducing GHG emissions. The grease trap (FOG) is readily available in Ireland, in response to mandatory grease trap installations for food service establishments in the EU. Food waste and organic waste are sources separated and collected in a separate bin for organic waste. Ireland’s major agro-industrial units such as wineries, breweries, distilleries, cheese factories, other food factories, and livestock units produce wastes, with high organic load, that could be used for anaerobic digesters in functioning WWTPs that produce biogas in significant quantities (Awe et al., 2017). Thus, co-digestion could be an opportunity for the water industry in Ireland to increase its renewable energy generation, without any additional facility. Revenue can be generated through gate fees or service charges. This could reduce the environmental footprint. At the same time, the application of co-digestion of FW with SS will help Ireland to meet the EU Landfill Directive (Council Directive, 1999), which requires the reduction of biodegradable waste in the landfill to 35% by 2020, based on the 1995 levels.

Finally, there is need to investigate the co-digestion dynamics of LCFAs, with a view to improving its lipid inhibition effects, because the AD of these wastes (FW and FOG) has a positive influence on the efficiency of biogas yield. This will allow a better understanding on synergy and negative effects of LCFAs degradation, with a view to determining better modification technique in term of quantity, mixing effects and frequencies of lipid waste addition for its adaptation and full implementation in the AD system.

5. CONCLUSIONS

The AD batch experiments were conducted to investigate the superiority of co-digestion of SS, FW, and FOG in various proportions. The results demonstrated that SS and FW mixtures (70:25, 50:45, and 45:50) with a mixture of 5% oil addition had the highest methane production with 771, 694 and 725 NmL CH\textsubscript{4}/g VS\textsubscript{added} respectively, significantly higher than mono-digestion. This translates to 123% (2.23 times) higher than SS and 80.14% (1.8 times) than FW alone for R10. Further, R12 and R13 were 100.58% (2.01 times) and 109.53% (2.1 times) higher than R2 (SS) and 62.15% (1.62 times) and 69.39% (1.69 times) for R3 (FW).

There was inhibition of VFAs, which could be overcome with a reduction in OLR and FW adjustment. The NH\textsubscript{4}+-N was (194 - 2294 mg/L), below the critical threshold 3000 mg/L. Anaerobic co-digestion is a viable technology for treating different organic waste streams and offers the possibility of simplifying and integrating domestic waste management.
At least 30% of AD unused capacity at WWTP could be available to treat and handle co-substrate for digestion. Therefore, if Ringsend WWTP can adopt 70:25:5 for their 30% unused capacity for co-digestion, their biogas production would increase to 100,350 m³/day of biogas according to the results obtained. This could translate into 36.6 million m³ of pure methane per year with an energy yield of 386,422,762 kWh (386.42 GWh/year), assuming 10.55 kWh equals 1 m³ CH₄ and 35% energy conversion efficiency of the generators. The suggested mixing ratios used in this study could also be adjusted to obtain more methane production for alternative energy purposes.

The study demonstrates the interaction effect between the feeding composition and anaerobic co-digestion performance. It provides meaningful insight for exploring the utilization of FW and FOG as strategies to reduce wastes, stabilize and enhance AD performance for the practical application. Co-digestion can contribute to renewable energy production, diversion of organic waste from landfill and reduce GHG emissions.

ACKNOWLEDGMENT

The first author acknowledges the support from the Civil Engineering Department of University College Dublin, partial scholarship support from Student Universal Support Ireland (SUSI).

REFERENCES


Awe, O. W., Liu, R., Zhao, Y. (2016) Analysis of Energy Consumption and Saving in Wastewater Treatment Plant: Case Study from Ireland, Journal of Water Sustainability, 6(2), 63–76.


Buswell, A. M., Neave, S. L. (1930) Laboratory studies of sludge digestion, Division of the State Water Survey.


