Hydrodynamic cavitation as a novel approach for pretreatment of oily wastewater for anaerobic co-digestion with waste activated sludge

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Abstract

Application of hydrodynamic cavitation (HC) was investigated with the objective of biogas production enhancement from co-digestion of oily wastewater (OWW) and waste activated sludge (WAS). Initially, the effect of HC on the OWW was evaluated in terms of energy consumption and turbidity increase. Then, several mixtures of OWW (with and without HC pretreatment) and WAS with the same concentration of total volatile solid were prepared as a substrate for co-digestion. Following, several batch co-digestion trials were conducted. To compare the biogas production, a number of digestion trials were also conducted with a mono substrate (OWW or WAS alone). The best operating condition of HC was achieved in the shortest retention time (7.5 min) with the application of 3 mm diameter orifice and maximum pump rotational speed. Biogas production from all co-digestion reactors was higher than the WAS mono substrate reactors. Moreover, biogas production had a direct relationship with OWW ratio and maximum pump rotational speed. Biogas production from all co-digestion reactors was higher than the reactors without pretreatment.

1. Introduction

Biogas production has been considered a source of renewable energy for many years in small- and full-scale installation. Production of biogas from sewage sludge has been a standard process since the 1930s and what has changed during these years is more related to efficiency, degree of complexity and specifications [1]. In general, typical digesters of wastewater sludge may recover 20–40% of the required energy of treatment plants with activated sludge processes [2]. Therefore, there is a major gap for providing all energy needs of wastewater treatment, which should be covered by developing some new methods. One available and well-known option is adding another organic waste with high biogas production potential as a co-substrate to the influent ("co-digestion"). These co-substrates for anaerobic digestion could be food waste, organic fraction of municipal waste, lipid-rich waste (grease trap sludge); and fat, oil and grease wastes (FOG wastes). Among all of the co-substrates, lipid rich and FOG wastes are the most interesting due to their high biogas and methane yield. According to guidelines of German engineers association, theoretical biogas yields for fats (C16H32O2), proteins (C13H25O7(N3S)), and carbohydrates ((CH2O)n) are 1390, 800, and 750 ml/g VS respectively. In addition, theoretical ratio of methane to carbon dioxide for biogas from fats is 72% to 28% which is much higher than methane content in biogas produced from proteins (60%) and carbohydrates (50%) digestion [3].

However, anaerobic digestion of lipid-rich substrates could be a challenging process, mainly because of some operational problems such as blockage of surface, pumps, and pipes, digester foaming, biomass floatation, and wash out. Basically, the main components of common oils (long chain fatty acids and triglycerides) are not soluble in water and after entering the reactor, they will float due to their density difference. This would lead to the operational problems and also reduces the contact surface between hydrolytic bacteria and the oily substrates resulting in a reduction of the reaction rate. For this reason, a pretreatment method should be applied to enhance the process and the production of biogas. In recent years, many pretreatment methods such as alkaline and enzymatic hydrolysis; acid treatment; heat and pressure; thermo-alkaline:
and ultrasound have been investigated. However, most of these methods require a lot of energy or chemicals which are not commonly favorable and the results are not satisfactory. Therefore, studies are needed for an effective and applicable pretreatment process.

One of the possible processes for enhancing biogas production from digestion of oily materials (waste or wastewater), is the application of cavitation on these substrates. Generally, cavitation can be defined as a process of nucleation, growth and implosion of cavity bubbles in a liquid [4]. This implosion of bubbles results in the formation of high-pressure spots and intensive shockwaves which create an extremely turbulent condition. This turbulence and the other effects of the cavitation could intensively mix insoluble liquids e.g. water and oil, which result in the formation of stable emulsions [5]. Cavitation mainly results from applying stretching forces or localized energy to a liquid. When the stretching forces are applied to a liquid, the local pressure could drop under the vapor pressure. Consequently, cavitation nuclei are formed in the liquid and then they grow and create cavitation bubbles. After releasing the forces, the cavitation bubbles compress and implode violently as the result of pressure recovery (ultrasonic and hydrodynamic cavitation) [6]. However, the application of localized energy supplies a significant amount of energy to small elements of the liquid volume. This leads to the increase of internal energy of the liquid elements up to a point which results in the phase change from liquid to gas and the formation of bubbles filled with vapor and gases. Following, when the bubbles leave the high energy zones due to the same implosion procedure they violently implode and disappear. Generally, this localized energy could be provided by a laser beam or a stream of heavy elementary particles such as protons. This process is called molecular or optical cavitation based on the source of applied energy [5].

Due to the complexity of the process and high operating costs of molecular and optical cavitation they have not found wide scale applications [5,7]. Ultrasonic cavitation has been commonly applied as an alternative way for the reduction of pollutants and other environmental issues for many years. However, ultrasonic technology has some negative points such as low energy transfer efficiency and restricted active cavitation zone near to the transducer [8,9]. As a practical alternative, hydrodynamic cavitation (HC) has been reported frequently as a more energy efficient method compared to acoustic cavitation [10–13].

The present study was conducted in two main parts with the aim of enhancement of biogas production from co-digestion of oily wastewater (OWW) and waste activated sludge (WAS). First, the effect of HC pretreatment on OWW was evaluated and then the co-digestion of OWW with WAS was investigated in batch reactors. To the best of our knowledge, the application of this pretreatment for enhancing OWW digestion has not been reported so far.

2. Materials and methods

2.1. Substrates and materials

In the present study oily wastewater was prepared by the addition of pure sunflower oil to drinking water, and a real sample was not used so that the fluctuations in substrate quality could be prevented. The oil contained 920 gram fat per liter and its calorific value was equal to 34,040 kJ/l (8280 kcal/l). This oil was a mixture of saturated and unsaturated fatty acids and consisted of 12% of saturated fatty acids, 27% monounsaturated fatty acids, and 61% of polyunsaturated fatty acids. To create OWW, based on the average FOG content of municipal grease trap wastes [14], the oil content was adjusted to 2% of the total mass.

WAS was collected from Uelzen (Lower Saxony, Germany) wastewater treatment plant (WWTP) which covers approximately 80,000 p.e. It was thickened using a belt thickener to reach a dry solid content around 4.5%. In addition, all of the batch reactors were inoculated with digested sludge with 1.66% dry solids and 61.6% of volatile to total solids ratio (VS/TS) from Uelzen WWTP.

2.2. Hydrodynamic cavitation

The HC setup was designed and built specially for this research and a simple flow diagram of that is presented in Fig. 1. The setup mainly included a storage tank (approximately 15 l), a vertical multistage centrifugal pump with 12 bar maximum head (Leo\texttrademark LVS1-19, China), a cavitation reactor, a control equipment (LS\textsuperscript{4} variable frequency drive, South Korea), a flow meter (Fischer\textsuperscript{5} rotameter, Germany), pressure gauges, and a main and bypass line (polyurethane high pressure tubes, with 8 mm of inner diameter). The OWW was taken out from the storage tank to the pump and then the pressurized discharge was branched to the main and the bypass line to have a better control especially in the startup. The OWW was conveyed through the main line to the cavitation reactor and then again to the storage tank. The cavitation reactor consisted of an inducer and a polypropylene cylindrical reaction chamber with approximately 1.5 l volume. Orifice plates were used as the inducer with 3, 4, and 5 mm in open diameter for different trials of this study and they were placed in the entrance of the cavitation chamber.

To determine the best operating condition of hydrodynamic cavitation device, the effect of three parameters was analyzed as independent variables according to Taguchi method. The variables included pump rotational speed (or electricity frequency of motor), retention time (the recirculating time of the OWW inside the HC device), and throat diameter. Then, the liquid temperature, the pressure drop, and the flow rate were monitored during all of the trials as dependent variables. For each independent variable, three levels were defined and accordingly, L9 array was chosen for the research design. Therefore, this part of research as it is described in Table 1 was planned in nine trials and one certifying trial (St1-T10).

To find the best operating condition, two parameters were measured as responses. First, turbidity as a criterion for analyzing emulsification effect was measured by light scattering method (Hach-Lange\textsuperscript{6}, Nephla turbidity meter, Germany). Through each trial, two samples were taken from the outlet of the HC device: one, after one minute of running with maximum pump speed and the other after the trial retention time with planned conditions. Due to the upper limit of the measurement device, the mixture was diluted 1:25 with tap water. After dilution, turbidity was measured and the difference between the records of the two samples was considered as the result. After the trial day, turbidity measurements were continued in 8 (day 1–7, and day 14) other days to investigate the turbidity reduction rate over time.

The second parameter was energy consumption during the cavitation trials and it was recorded by means of the variable frequency drive of the pump. All the measurements were duplicated and the results were analyzed by Qualitek-4 software.

2.3. Batch co-digestion

Batch fermentation setup used for this study was built according to DIN 38414 part 8 and as it is shown in Fig. 2, the biogas volume was measured based on liquid displacement. To evaluate the effect of OWW concentration in the substrate, six compositions of substrate materials (OWW and WAS) all with the same mass of volatile solids (VS) were planned for batch digestion trials. These compositions were created according to six ratios of OWW/total VS of the substrate which were equal to 0%, 20%, 40%, 60%, 80%, and 100%.
To set up the reactors, first 300 ml of inoculum, Uelzen WWTP digested sludge, was added to all of the main (fed with HC pretreated OWW) and control (fed with raw OWW) reactors. Then, according to the planned substrate composition for each reactor, the calculated amounts of WAS were added to the reactors (except the reactors which were fed with 100% of OWW). Following, according to the substrate composition, calculated amounts of pretreated OWW, were added to the main reactors. The same amount of oil which had been added to the main reactors was added to the control reactors in the form of raw oil. Therefore, to have a similar condition, tap water was also added to the control reactors with the same amount of the water which had been added to the main reactors in the form of OWW. According to the guidelines of association of German engineers [3], the ratio of VS_{substrate}/VS_{inoculum} was adjusted to 0.5 and the measurement of the total and organic solids was conducted according to DIN 38409 T2 and 38414 T3 respectively. All of the batch reactors were placed in a climatic chamber with mesophilic temperature (37 ± 1°C) and the produced biogas was collected in the glass cylinders filled with acidified water. The tests were terminated when the daily biogas rate was equivalent to or less than 1% of the cumulative biogas production.

Totally, 6 batch digestion trials were planned to cover the different ratios of pretreated OWW and WAS. In addition, to investigate the effect of the HC pretreatment, parallel trials were conducted without HC pretreatment for OWW. Moreover, one batch trial without any feed was also set up as reference samples (blank) for the measurement of biogas production of the inoculum. All of the batch trials were duplicated and the average results were recorded.

### 3. Result and discussions

#### 3.1. Hydrodynamic cavitation

##### 3.1.1. The optimum operation

The effect of hydrodynamic cavitation on synthetic oily wastewater was investigated and the results from different operating conditions were compared in terms of emulsifying and energy consumption by Qualitek-4 software. To investigate the emulsification effect of HC, turbidity changes were considered as the first response. Moreover, to find a balance between the cavitation effect and the required energy, the consumption of energy was considered as the second response. The same weights were allocated for these two responses and the best and worst values (needed for analyzing) were chosen from obtained results which are all presented in Table 2. In addition, the hydraulic characteristics of the HC device has been presented in Table 2 by a dimensionless parameter described as the cavitation number (C_v), which can be defined as follows [15]:
\[ C_v = \frac{2(P_d - P_m)}{\rho V^2}; \]

where \( P_d \) and \( P_m \) are the downstream and vapor pressure, respectively; \( \rho \) is the density of the liquid; and \( V \) is the velocity near the orifice.

Based on the results, the optimum operating conditions would be achieved with a maximum pump rotational speed, 7.5 min of retention time, and 3 mm throat diameter. According to the modeling outcomes, the expected result for this operating conditions (with the integration of results) should be 88.163. After conducting the certifying trial (St1-T10), the integrated result was 4\% less than the predicted value. Nevertheless, it was still the highest value among the other trials. Also, the smallest cavitation number (0.38) was obtained in this operating condition which means it had the highest extent of the cavitation among all the other trials.

### 3.1.2. Stability of the HC effect

After the HC pretreatment, due to density difference of emulsion ingredients, some oily droplets floated over time. Concerning this effect, turbidity was chosen to be monitored for analyzing the trend of demulsifying. The turbidity was measured two weeks after the cavitation trials. The overall results as presented in Fig. 3 determined that the turbidity of pretreated OWW decreased strongly during the first days following the cavitation pretreatment. However, this trend was not constant and it didn’t lead to complete demulsifying. The main part happened during the first day. In the second day, the reduction slowed down and the turbidity stayed more or less constant.

Generally, droplets size is one of the most important parameters for the stability of a water and oil emulsion [16]. Therefore, this reduction in turbidity could mainly be related to re-formation of bigger size oily droplets or to coalescence effects. In the research work of Tang and Sivakumar [17], the effect of HC was investigated on the long-term stability of multiple oil-in-water emulsions. Their results suggested that higher operating pressure for cavitation and number of circulation in the emulsification process could enhance the stability of submicron emulsions. Similarly, in our experiments and as it can be resulted from Fig. 3, the trial with 32 circulations and 8.5 bar of operating pressure (St1-T9) had the highest stability mainly because it had the highest combination of the two factors.

However, for anaerobic digestion of OWW, long-term emulsion stability is not basically necessary. Because the hydrolysis of lipids as a first order reaction has a kinetic constant between 0.08 and 1.7 d\(^{-1}\) [18]. Therefore, considering the average kinetic constant for a real OWW which is a mixture of different lipids in a general situation, the essential time for lipid hydrolysis would also be near one day. So, long-term emulsion stability would not be necessary and it is better to reduce the number of circulations like the certifying trial (St1-T10) to reduce the energy consumption. Though, it is essential to insert the emulsion to the digester immediately after HC pretreatment.

### Table 2

Summary of results for HC pretreatment of OWW.

<table>
<thead>
<tr>
<th>Trial code</th>
<th>Turbidity increase (%)</th>
<th>Energy consumption (kW h)</th>
<th>Flow (l/h)</th>
<th>Number of recirculation</th>
<th>Operating pressure (bar)</th>
<th>Integrated results</th>
<th>Velocity at the throat (m/s)</th>
<th>Cavitation number</th>
</tr>
</thead>
<tbody>
<tr>
<td>St1-T1</td>
<td>88.25</td>
<td>0.056</td>
<td>500</td>
<td>4.2</td>
<td>6.5</td>
<td>80.56</td>
<td>19.7</td>
<td>0.51</td>
</tr>
<tr>
<td>St1-T2</td>
<td>22.69</td>
<td>0.125</td>
<td>750</td>
<td>12.5</td>
<td>5.5</td>
<td>46.15</td>
<td>16.6</td>
<td>0.72</td>
</tr>
<tr>
<td>St1-T3</td>
<td>13.04</td>
<td>0.265</td>
<td>1050</td>
<td>35.0</td>
<td>3</td>
<td>26.46</td>
<td>14.9</td>
<td>0.89</td>
</tr>
<tr>
<td>St1-T4</td>
<td>49.60</td>
<td>0.094</td>
<td>850</td>
<td>7.1</td>
<td>7.2</td>
<td>60.57</td>
<td>18.8</td>
<td>0.56</td>
</tr>
<tr>
<td>St1-T5</td>
<td>31.98</td>
<td>0.213</td>
<td>1275</td>
<td>21.3</td>
<td>4.2</td>
<td>40.1</td>
<td>18.0</td>
<td>0.61</td>
</tr>
<tr>
<td>St1-T6</td>
<td>93.48</td>
<td>0.323</td>
<td>550</td>
<td>18.3</td>
<td>8.5</td>
<td>52.61</td>
<td>21.6</td>
<td>0.42</td>
</tr>
<tr>
<td>St1-T7</td>
<td>49.84</td>
<td>0.138</td>
<td>1420</td>
<td>11.8</td>
<td>5</td>
<td>55.71</td>
<td>20.1</td>
<td>0.49</td>
</tr>
<tr>
<td>St1-T8</td>
<td>136.09</td>
<td>0.210</td>
<td>580</td>
<td>9.7</td>
<td>10.25</td>
<td>82.62</td>
<td>22.8</td>
<td>0.38</td>
</tr>
<tr>
<td>St1-T9</td>
<td>86.84</td>
<td>0.500</td>
<td>950</td>
<td>31.7</td>
<td>8.5</td>
<td>62</td>
<td>21.0</td>
<td>0.44</td>
</tr>
<tr>
<td>St1-T10</td>
<td>111.16</td>
<td>0.105</td>
<td>580</td>
<td>4.8</td>
<td>10.25</td>
<td>84.35</td>
<td>22.8</td>
<td>0.38</td>
</tr>
</tbody>
</table>
3.2. Batch experiments

3.2.1. Biogas production

The effect of OWW ratio in substrate (0%, 20%, 40%, 60%, 80%, and 100% of fed volatile solids) on batch anaerobic digestion was investigated and the obtained results were analyzed in terms of biogas production and reaction rate. During the batch experiments, biogas production was recorded and standard gas volume was calculated by eliminating the effects of temperature, organic loading, moisture, and air pressure fluctuations. The final quantities of produced biogas are presented in Table 3.

According to the obtained results, the increase of the OWW ratio led to the increase of biogas production and no inhibition was detected in any of the trials. In addition, similar results were reported from other studies concerning batch co-digestion [19,20]. In the study conducted by Davidsson et al. [19], the biogas production from several mixtures of grease traps sludge and sewage sludge (10:90, 25:75 and 60:40 respectively on VS basis) was evaluated. The highest methane yield obtained from the 60:40 trial was 110% higher than the methane yield from digestion of sewage sludge alone. Similarly, in our experiment the biogas yield from the trial with 60% OWW ratio was 115% higher than the biogas yield from digestion of WAS alone. However, the highest biogas yield (from co-digestion) obtained from the trial with 80% OWW ratio was 190% (or 3.4 times) higher than the digestion of WAS alone. This higher biogas yield could be related to the higher OWW ratio,

![Graph](image)

Fig. 3. (a) Turbidity reduction of pretreated OWW and (b) turbidity reduction of certifying trial in the first 24 h.
which had a higher biogas potential compared to WAS. In the same way, the biogas yield from the trial with mono OWW substrate (100% OWW) was 215% higher than the digestion of WAS alone.

<table>
<thead>
<tr>
<th>OWW ratio of total VS in substrate (%)</th>
<th>HC pretreated OWW</th>
<th>Raw OWW</th>
<th>Biogas yield increase by HC pretreatment (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Biogas yield (ml/gVS)</td>
<td>Estimated biogas yield just from OWW (ml/gVS)</td>
<td>Biogas yield (ml/gVS)</td>
</tr>
<tr>
<td>0</td>
<td>319.6</td>
<td>319.6</td>
<td>–</td>
</tr>
<tr>
<td>20</td>
<td>451.0</td>
<td>976.7</td>
<td>421.4</td>
</tr>
<tr>
<td>40</td>
<td>645.4</td>
<td>1134.2</td>
<td>540.1</td>
</tr>
<tr>
<td>60</td>
<td>894.2</td>
<td>1277.3</td>
<td>687.5</td>
</tr>
<tr>
<td>80</td>
<td>1089.2</td>
<td>1281.6</td>
<td>928.0</td>
</tr>
<tr>
<td>100</td>
<td>1307.1</td>
<td>1307.1</td>
<td>1009.9</td>
</tr>
</tbody>
</table>

Fig. 4. Reaction constant for batch reactors; (a) the final $K$ value and (b) the $K$ value after one week of digestion.

HC pretreatment also improved the biogas production in all of the trials. The maximum increase was 30% and it was obtained from the trial with 60% of OWW ratio. These results are also in accordance with results reported by Padoley et al. [21], who
investigated the effects of the HC pretreatment on a distillery wastewater. They reported that the application of HC pretreatment could enhance the wastewater biodegradability and increase the biogas formation by almost 6-fold. In comparison with ultrasonic pretreatment and based on the results of Luste et al. [22] and Li et al. [23], who pretreated grease trap sludge and FOG waste (67% of fed VS) with ultrasound (24, 20 kHz) respectively, the application of HC was a more effective way for preparing lipid-rich wastewaters for digestion. In both of these two studies, the ultrasonic pretreatment could not improve the biogas production from batch digestion reactors. Also, the obtained results from other pretreatment methods were not so impressive. Thermo-alkaline pretreatment could slightly enhance biogas production and in only some cases it improved the reaction rate [23–25]. Carrere et al. [25] reported 4–7% increase in methane production for a range of pH from 8 to 10 and a range of temperature from 80 °C to 120 °C. But, the application of thermal pretreatment even had a negative effect on biogas production in many cases which could be related to potential of formation of recalcitrant compounds [26]. In the study of Carrere et al. [25] thermal pretreatment (170 °C) resulted in 17% drop in methane potential. Such results were also reported for thermal pretreatment with lower temperature (70 °C for 1 h) [22].

3.2.2. Energy balance
A general question about the pretreatment methods for anaerobic digestion is if they could be applicable due to energy balance. The energy consumption through HC for the optimum condition was equal to 105 Wh (watt per hour) for 15 l of the recirculating liquid (or 7 Wh/l). Based on the estimated data for biogas production only from OWW, the biogas increased 27% (or 251 ml/gVS) on the average with the application of HC. Also, with respect to 72% methane yield of fat [3] and 891 kJ/mol standard enthalpy of methane combustion [27], the extra potential energy production would be 2 Wh per gram of volatile solids (Wh/gVS). The oily wastewater had 2% of volatile solids; therefore, the potential energy outcome from this would be 40 Wh/l which is almost 6 times the consumed energy for the HC pretreatment. In contrast with other pretreatment methods like ultrasound or thermo-alkaline, HC needs much less energy and provides a higher increase in biogas production. As an example, to reach only 6% increase in methane yield (from 542 to 576 ml/gVS) the temperature of the substrate (67% (vol) grease trap sludge and 33% (vol) waste activated sludge) was increased to 80 °C which is 43 °C higher than the mesophilic temperature. Therefore, this pretreatment needs almost 50 Wh/l energy which is much more than the recovered energy by extra methane production. About HC pretreatment, it should also be mentioned that this energy consumption belongs to a lab scale HC device and less energy consumption could be expected from a larger scale device.

3.2.3. Reaction rate
The effect of pretreatment also could be observed in biogas production rates. So, for all of the trials, the reaction kinetic constant (K) was calculated as a first order reaction for two time periods (total reaction time and the first week of digestion). The total reaction rates of all the co-digestion and OWW mono substrate trials (with or without pretreatment) as presented in Fig. 4 were higher than the rates of WAS digestion alone. Therefore, it could be concluded that the digestion of this OWW was simpler and faster than the WAS alone. In Fig. 4a the total reaction kinetic constants of all the trials are presented and they show that the HC pretreatment in general also increased the final reaction rates. In other words, the HC pretreatment could also speed up the digestion.

To have a better overview on the digestion progress, the kinetic constants of the first week are also presented in Fig. 4b. Similar to the total reaction rates, all of the co-digestion trials with HC pretreatment had much higher rates than the trials without pretreatment. The rates also increased with the increase of OWW ratios, so that the maximum rate was observed for the 80% OWW ratio. As it was mentioned, this could also be related to the better degradability of pretreated OWW in comparison with WAS.

However, as presented in Fig. 4b, the first week reaction rate of the OWW mono substrate trial (100% OWW) was much less than all of the other trials. To be sure about the result, this trial was repeated and the obtained result was more or less the same. From the total reaction rate and the ultimate biogas production, it could be concluded that the increase of OWW ratio in the substrate would not lead to a major and permanent inhibition or rate reduction. However, curves of cumulative biogas diagram (Fig. 5) shows

**Fig. 5.** Cumulative biogas production of reactors which fed just with OWW.
a temporary lag phase during the first week of digestion for this trial. This lag phase could be related to higher hydrolysis rate of the reactors with HC pretreatment which might lead to high concentrations of volatile fatty acids in reactors with a high ratio of OWW. This may exceed the consumption capacity of them. Consequently, this higher concentration of fatty acids could lead to temporary inhibition by affecting the syntrophy of anaerobic digestion. This syntrophy is a mutualistic interaction between obligate hydrogen producing acetogens (OHPA) and hydrogen-removing bacteria (e.g. methanogens and sulfate-reducing bacteria), which could be interrupted by high concentrations of fatty acids [28]. The temporary inhibition showed itself by rate reduction in the beginning of the digestion. But in the following days the reactors were recovered and despite the lag phase, the ultimately produced biogas was 29% percent more than the reactors without HC pretreatment.

The effect of FOG substrates pretreatment on digestion rate was also investigated in the other studies. Luste et al. [22] and Li et al. [23] reported a longer lag phase after applying the ultrasound while thermal and thermo-alkaline treatment could accelerate the FOG digestion [22–25]. The reason for this negative effect of ultrasonic pretreatment on FOG digestion is not completely clear. As a possible reason which caused that inhibition, Luste et al. [22] suggested the formation of long chain fatty acids, while Li et al. [23] introduced decrease in acetic acid concentration by the application of ultrasound.

4. Conclusion

According to the obtained results, it could be concluded that the HC pretreatment is an effective method for the enhancement of biogas production from co-digestion of OWW and WAS. This process could improve the total biogas production up to 30% and could generally increase the reaction rate of the co-digestion process. The highest increase in biogas production was obtained from the trial with 60% OWW ratio while its reaction rate among the other trials was not the highest. Therefore, it could be concluded that the highest increase in the biogas production would not necessarily lead to the highest increase in the reaction rate by the application of HC. The consumed energy for this process was only 7 Wh/l and it could increase biogas production almost 20–30% which is 6 times more than the consumed energy on the average. Generally, no major inhibition could be detected and only a longer lag phase of reactors with very high OWW ratio could be counted as the only sign of possible inhibition. In comparison with the other pretreatment methods which were evaluated in the other studies, the HC had a stronger effect on enhancement of biogas production and reaction rate. Also, it is more economically justifiable due to its low energy consumption. However, in comparison with the ultrasonic or other pretreatment methods, the HC setups are not easily accessible at the moment and this could be counted the main weakness for application of this process.

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Appendix A

To calculate the energy production from OWW, first the volume of produced biogas from OWW was estimated for each reactor by eliminating the biogas from WAS and then the calculations were performed as follows for the trial with 40% OWW fraction as an example:

Biogas yield from WAS \( Y_{WAS} \) = 319.6 ml/gVS

Fraction of WAS in the substrate \( F_{WAS} \) = 1 – 40% = 60% of VS

Biogas from WAS fraction \( G_{WAS} \) = \( Y_{WAS} \times F_{WAS} \) = 319.6 \times 60\% = 191.8 ml

Total biogas from 40% OWW trial \( G_{40\%} \) = 540.1 ml/gVS

Fraction of WAS in the substrate \( F_{OWW} \) = 40%

Biogas yield from OWW fraction \( Y_{OWW} \) = \( (G_{40\%} - G_{WAS})/F_{OWW} \)

\( Y_{OWW} \) Without HC = \( (540.1 - 191.8)/0.4 \) = 870.8 ml/gVS

\( Y_{OWW} \) With HC = \( (645.4 - 191.8)/0.4 \) = 1134.2 ml/gVS

Percentage of biogas yield increase by application of HC = 30.2%

After repeating the same calculation for other trials, the average increase of biogas yield was obtained equal to 27% or 251 ml/gVS.

Then, considering 72% of methane content for anaerobic digestion of fat, the extra obtained energy could be calculated as follows:

\[ E_r = (\frac{251}{1000} \times 72\%) \times 891 \text{ kJ/mol} = 7.19 \text{ kJ/gVS} \] or 2.0 (Wh/gVS)

References


