COMPARING THE PERFORMANCE OF THERMOPHILIC AND MESOPHILIC ANAEROBIC DIGESTION OF THP Pre-treated Sewage Sludge


Abstract

Robust anaerobic digestion process performance depends on digester temperature, substrate quality, organic loading rate, retention time and the availability of skilled operator involved. This applies to both thermophilic anaerobic digestion (THAD) and mesophilic anaerobic digestion (MAD) processes. Historically, THAD process is predominantly used as a pre-treatment process based on a shorter hydraulic retention time (HRT). A standalone longer HRT THAD process had also been used at the lower end of the thermophilic temperature range, but due to increased heat requirements of the process, its use had been limited. Recently, however, the use of Thermal Hydrolysis Process (THP) to pre-treat sludge feed has significantly increased, resulting in the availability of significant amount of low grade heat which has to be removed to ensure the effective operation of the MAD process.

In this paper, the performance of THAD of THP pre-treated sludge was investigated in comparison with that of THP+MAD process, used as a control, within temperature ranges of 45 – 56 °C and 42 °C respectively.

The results obtained from laboratory scale experiments showed that the THAD process achieved an overall long-term average VSr range of 50 - 55%, overall biogas production of 420 m3/tonne dry solids (TDS).

Keywords

THP, mesophilic, thermophilic, anaerobic, digestion, bacteria, sludge, hydrolysis

Introduction

Anaerobic digestion is one of the oldest wastewater treatment process unit operations and is an essential tool for converting potential pollutant organic wastes to useful by-products and protecting the environment and public health.

It is now recognised, that anaerobic digestion process converts potential pollutant organic substrates to economically useful by-products such as biogas and digestate.

This offsets some of the expenditure invested to treat the wastewater. It also offers a public health (sanitation) benefit by eliminating odour, killing pathogens and preventing the spread of diseases. This particularly applies to industrialised countries of Europe and some parts of America.

A retrospective view and current state on the use of low and high temperature range thermophilic anaerobic digestion of thermally hydrolysed sewage sludge in comparison with mesophilic anaerobic digestion was given in Shana et al. (2016).

Therefore, no additional extensive literature review was included in the present paper, but if needed a reader is guided to an up-to-date literature review on current topic in Shana et al. (2016).
This paper is an extension to the previous paper by Shana et al. (2016) that reported thermophilic anaerobic digestion of thermally hydrolysed sludge in the temperature range of 46 – 50°C, whereas the current paper adds data obtained from 52 – 56°C.

The most important operational factors that can significantly affect the robustness of an anaerobic digestion process performance are digester temperature, substrate quality, organic loading rate, retention time and operator’s skill. The most important of all is the operator’s skill. An operator is the one who makes operational changes, i.e., controls and maintains the required digester temperature, organic loading rate, and retention time as well as keeps the sludge well mixed.

The operator skill attributes such as knowledge of anaerobic digestion process, attitude, ownership and team work spirit are essential ingredients for a successful anaerobic digestion process and the quality of the data obtained.

Poor operational skill (an external factor) can often be taken for inadequate anaerobic digester performance process caused by the malfunctioning of bacteria population in a digester or poor quality substrate being fed. The lack of knowledge on anaerobic digestion process, inconsistencies in digester feeding regime, indifference or lack of ownership, and constant reactive work by untrained operators can cause significant damage to anaerobic digestion process.

Anaerobic digestion process is a biotechnology that requires the leadership of skilled technical personnel and should be only run by a well-trained and proactive minded team of technicians. Even the involvement of a single untrained operator in a team, if allowed to run the anaerobic digestion process, can cause a prolonged setback to sustainable anaerobic digestion process performance.

**Materials and methods**

Substrate source, experimental set-up and characterisations of chemical and physical properties were extensively reported in Shana et al. (2016).

**Results and discussion**

**Hydraulic retention time (HRT days)**

Figure 1 show the digester HRTs of THAD and MAD processes.

Initially, both THAD and MAD processes were operated at 16 days HRT for a minimum of 3HRTs (48 days) and monitored before increasing the temperature of TAD to 47°C while keeping the temperature of MAD control digester constant at 42°C (Shana et al., 2016).
Figure 1: Hydraulic retention time in days in the anaerobic digestion types investigated

Figure 1 also shows that after 3HRT, the digester HRT was reduced to 13 days regardless of digester temperatures used.

The performance of a digester can be well managed if HRT is properly controlled and used; HRT determines a correct and stable food to biomass ratio (Shana et al., 2016).

The HRTs used in this investigation is much longer than that used for full scale THAD process (for example typically 1 – 3 days for sludge pre-treatment, Lu and Ahring, 2007 cited in Shana et al., 2016).

Digester Volatile solid input and output

Figure 2 shows the digester feed and digested sludge volatile solids content obtained from the THAD and MAD processes over a period of 70 weeks.
The data in Figure 2 shows that the THP hydrolysed sludge feed volatile solids ranged from 80 – 85%. Figure 2 also shows the digested sludge volatile solids content ranging from 70 – 73% regardless of digestion temperature used.

Previous work by Shana (2015), showed that when digesters were fed with THP hydrolysed sludge feed consisting of 76%-77% volatile solids content, its volatile solid content was reduced to 61 -65% in the digestate.

This equates to a reduction of about 12 – 15 percentage point. The data gathered during this research showed a similar range of VS% reduction and concurred with the findings of Shana (2015) cited in Shana et al. (2016).

**Volatile solids loading rate**

Figure 3 shows the digester volatile solids loading rate (VSLR) in the THAD and MAD processes over a period of 70 weeks.

There was a slight variation in the VSLR in both THAD and MAD processes mainly due to variations in the digester dry solids content throughout the duration of the trial; may be caused by the degree of variations in the sludge hydrolysis process used.
Volatile solids loading rate used in the anaerobic digestion types investigated

THAD and control MAD digesters were operated on a volatile solids load rates ranging between 3.6 and 5.45 kg VS m\(^{-3}\)day\(^{-1}\). Average volatile solids load rate for both THAD and that of MAD digestion processes was 4.6 kg VS m\(^{-3}\)day\(^{-1}\).

These results indicated that both digesters showed a stable digestion processes when low as well high VSLR were used. Therefore, it is beneficial to feed THP-hydrolysed sludge without cooling to THAD, hence avoiding the requirement for cooling the hydrolysed sludge to the mesophilic digestion temperature range.

Volatile solid destruction

Figure 4 shows the sludge volatile solid reduction (VSr) during THAD and MAD temperature ranges investigated over a period of 70 weeks.

It is important to note that not necessarily a high VSR means high amount biogas production. As it can be seen later, some of the VSR achieved can be left as high VFA residue in the digesting sludge.
The VSr in the both THAD and MAD processes ranged from 50 -66% except where significant digestion process setback was observed between week 39 – 44 as well as weeks 65 -70 due the involvement of unskilled operators.

After 6 weeks of instability, the digesters recovered but again another setback was experienced. This took much longer time to recover regardless of the digestion type used. Despite this, the overall VSr in the THAD process shows the potential benefit to be had when running THP hydrolysed sludge under thermophilic anaerobic digestion condition.

**Volatile fatty acids production**

Figure 5 shows the amount of VFA in the thermally hydrolysed sludge feed, THAD and MAD digested sludges. The VFA of THP hydrolysed sludge feed averaged about 2,643 mg/l.

This VFA was significantly reduced during THAD and MAD anaerobic digestion processes.

However, from week 35 onwards there was build-up of VFA in THAD sludges. This also coincided with the inclusion of unskilled personnel in the running of these digesters.

The VFA build up in the digesters got worse from week 50 to week 70 and beyond. Although the performance has begun to improve after week 70 when better trained personnel were appointed.
Figure 5: Volatile fatty Acid content monitored in the sludge feed and anaerobic digestion types investigated

It can be seen that the VFA content of MAD digested sludge averaged 100 mg/l and THAD averaged 2000 mg/l over the 70-week period respectively (Table 1 and Figure 5).

The relatively high amount of VFA left in the THP hydrolysed digested sludge could be a useful tool during anaerobic digestion process as it mitigates the impact of high alkalinity detected due to high organic volatile solid used in the digesting sludge and gives a reasonable amount of VFA to alkalinity ratio in the digesters (Shana et al., 2016).

However, between weeks 50 to 70, a clear setback in the digestion process was noticeable again for the known reason mentioned before.

This data clearly demonstrates the importance of digester operational parameter being maintained closely and above all, the availability of well-trained technician in running an anaerobic digestion process.

Alkalinity production

Figure 6 shows the amount of alkalinity in the thermally hydrolysed sludge feed as well as THAD and MAD digested sludges monitored over 70 weeks period.

All the digestion types used showed uniform trend in alkalinity content during times of trouble as well as stable digestion process.

However, the alkalinity content of THAD process is much pronounced than MAD process, possibly due to higher protein conversion to ammonium bicarbonate which is a predominant form of alkalinity in an anaerobic digestion process.

Furthermore, from figure 6, it can be noticed, that the alkalinity was lower between weeks 57 and 70 during which the VFA concentration in the digesters used was enhanced as shown in figure 5 above.
This shows that the high VFA content of the digesters that begun in week 52 started to eat away the alkalinity content of the digesters and the digester buffering capacity was plummeted during weeks 57 to 61, when the process started to recover.

In this case, due to bad operational skill involved, the buffering capacity of all digesters was compromised.

**Figure 6:** Alkalinity content monitored in the sludge feed, THAD and MAD processes over a period of 70 weeks

The alkalinity increased by 3.1 - 3.9 times in different thermophilic digestion temperature ranges investigated when compared to the alkalinity content of the digester feed regardless of digestion types used.

The average alkalinity data found in the digested sludge at discreet operating temperatures of 42°C, 46°C, 47°C, 48°C, 49°C, 50°C, 52°C, 53°C, 54°C, 55°C and 56°C were 7030, 9173, 8446, 9558, 10, 220, 10,012, 9832, 10200, 10573, 11102 and 8500 mg/l respectively.

These high digesting sludge alkalinity content and relatively high VFA residual in the digesting sludge often gives a balanced environment in the anaerobic digestion process, effectively allowing a good methanogenic bacteria activity.

Therefore, the balance of these to two digestion process parameters is very important in maintaining a stable anaerobic digestion process condition (Shana et al, 2017) and their reaction is expressed in digesting sludge pH.

**VFA to Alkalinity ratio**

Figure 7 shows the VFA to alkalinity ratio in the THP-treated sludge feed as well as THAD and MAD digested sludges monitored over a period of 7 weeks.
The VFA to alkalinity ratio is an important tool to be used for anaerobic digestion process management. From this, it could be inferred, how well or badly the anaerobic digestion environment is functioning. The VFA to alkalinity ratio can only be measured if the data for both VFA and alkalinity is available. For data quality purpose, samples need to be analysed in a freshly digesting sludge and prolonged sample storage time may provide an erroneous data and a decision taken based on such a data could be costly.

It is an acknowledged fact, that when the VFA to alkalinity ratio exceeds 0.4, the anaerobic digestion process is considered as deteriorating.

The powerful story that the VFA and alkalinity ratio tells can be easily understood by just carefully glancing at the VFA to alkalinity ratio of the sludge feed shown in figure 7. It shows that the sludge feed VFA to alkalinity ratio is uniformly high throughout the experimental period. Whereas, the THAD and MAD treated sludge VFA to alkalinity ratio varied significantly over the experimental period. Once again, the enhanced VFA to alkalinity ratio of THAD and MAD treated sludges from week 51 onwards substantiates the importance of the operative’s skill mentioned earlier.

The data from week 1 to week 50 in Figure 7 shows, the VFA to alkalinity ratio of 0.03, 0.09, 0.03, 0.03, 0.03 and 0.09 in all the anaerobic digester types operated at all temperatures of interest and is an indicative of stable anaerobic digestion process (Shana et al, 2016).

The VFA to alkalinity ratio in the feed sludge ranged from 0.5 to 1.4, indicating the availability of high amount of volatile fatty acids in the feed compared to the sludge alkalinity content.

pH

Figure 8 shows pH of the THP pre-treated feed, THAD and MAD digested sludges.
Figure 8: pH monitored in the sludge feed and anaerobic digestion types investigated

The sludge feed and digested sludge pH measured shows the extent of interaction between sludge VFA and alkalinity contents.

pH is an indicator parameter for the chemical reaction that took place in the anaerobic digestion process; it shows the environment. Therefore, controlling the digestion process merely based on pH data is futile and it should be only used in conjunction with a VFA and alkalinity data. The availability of higher VFA and lower alkalinity in the digestion environment often brings about a reduced pH and vice versa.

The data in Figure 8 shows relatively stable THAD and MAD processes, but it didn’t clearly show digester instability between weeks 51 to 70, while the data for total VFA (fig 5) and VFA to alkalinity ratio (fig 7) well demonstrated the anaerobic digestion process instability.

The digester pH at 42°C, 46°C, 47°C, 48°C, 49°C, 50°C, 52°C, 53°C, 54°C, 55°C and 56°C had an average pH of 7.9, 7.8, 7.9, 8.0, 8.0, 8.1, 8.1, 8.1 and 8.1 respectively. The higher pH value reported may be due the result of high amount of sludge organic protein degradation to Ammonium and its subsequent conversion to its Ammonium bicarbonate (the source of alkalinity in anaerobic digestion process).

The data obtained are very similar to the pH values obtained during THP hydrolysed and MAD processed sludges reported by Shana (2015) cited in Shana et al. (2016).

Digester Ammonical nitrogen content

Figure 9 shows the ammonical nitrogen concentration in the THAD and MAD digested sludges monitored during the experimental period of 50 weeks. During weeks of 51 – 70, no ammonical nitrogen data were gathered due to anaerobic digestion process instabilities caused by operational issues mentioned earlier.
The data obtained from this work showed an elevated ammonical nitrogen concentration in all the digestion temperatures investigated, however, no detrimental effect to methanogenic bacteria was observed in all the digestion types used as indicated by stable biogas production regardless of the digester temperatures investigated (Shana et al., 2016).

The data in Figure 9 shows that the average ammonical nitrogen concentration in the THAD processes was 3,050 mg/l and that of the MAD process was 2,899 mg/l. During the weeks of 26 and 27, the digesters were accidentally slightly overfed and that caused elevated concentration in all the digestion processes.

This caused a minor corresponding reduction in the biogas yield but not determent to the overall anaerobic digestion process (Shana et al., 2016). There is a general view that when the ammonical Nitrogen concentration is allowed to increase above 3000 mg/l, it could be harmful to methanogenic bacteria and in this case measures had to be taken to reduce it to below this threshold figure. However, experience also shows us that given the digester feeding regime was stable; the anaerobic digestion process can function well even if the ammoniacal nitrogen concentration was much higher than the expected 3000 mg/l ammoniacal nitrogen threshold value.

Ammonia stays in the liquid state as ammoniacal nitrogen in the digested sludge below pH of 9.24 and become volatile above this value. Ammonia in the gas phase is much more toxic to bacteria than ammoniacal nitrogen in the solution (Shana, 2015).

As none of the pH values measured in the digestion types used in this experiment were exceeding the toxic value of pH mentioned above, it could be concluded that the digestion process instability experienced between weeks 51 - 70 is merely down to operational shortfalls.

The data obtained in this work was similar to the data reported by Sung and Liu (2003), where an increase of ammoniacal nitrogen concentration in both thermophilic and mesophilic digestion was observed (Shana et al., 2016).
Gas production

In this work the biogas production from THAD and MAD processes was measured in terms of biogas yield and specific biogas production.

Biogas yield

Figure 10 shows the biogas yield obtained from THAD and MAD of thermally hydrolysed sludge monitored over 70 weeks of experimental period.

The data in Figure 10 shows digester operation at temperatures of 42°C, 46°C, 47°C, 48°C, 49°C, 50°C, 52°C, 53°C, 54°C, 55°C, 56°C and corresponding average biogas yield of 409, 405, 465, 427, 423, 400, 412, 410, 350, 430 and 350 m3/TDS fed respectively.

The data shows that THAD process at 47°C and 55°C produced enhanced biogas yield, however, all thermophilic digestion temperature performed as well as control mesophilic digester. The biogas yield calculated in most thermophilic digesters temperatures showed slightly higher values than conventional MAD, but not significant enough to indicate digestion process superiority.

The data obtained from this work is in agreement with Palatsi and colleagues (2009) who tested a range of temperatures on cattle manure and mixture of primary and SAS obtained from wastewater treatment processes (Shana et al, 2016). These authors did not find a significant difference between the thermophilic and mesophilic digesters.

Specific biogas production

Figure 11 shows the specific biogas production obtained from THAD and MAD processes investigated over a period of 70 weeks. Specific biogas production is a measure of bacterial activity and the ability of the bacteria to convert the substrate to biogas; it is an indirect measure of the robustness of the bacteria population.
Figure 11: Weekly average specific biogas production data obtained from the anaerobic digestion types investigated

The data in Figure 11 and Table 1 show that anaerobic digestion processes run at 42°C, 46°C, 47°C, 48°C, 49°C, 50°C, 52°C, 53°C, 54°C, 55°C, 56°C provided specific biogas production of 0.8, 0.6, 0.8, 0.9, 0.9, 0.8, 0.8, 0.8, 0.8, 0.8 and 0.5 m³/kg VS destroyed, respectively.

The data also shows that the THAD processes performed as well as the MAD control digester indicating the viability of the thermophilic anaerobic digestion process. The specific biogas production data calculated from this work is slightly less than the often quoted and used engineering design value 0.9-1 m³/kg VS destroyed. Therefore, it is recommended to use a specific site values monitored than the use of commonly cited literature value particularly for design purposes.

Gas composition

Biogas Methane Composition

Figure 12 shows the biogas methane composition during THAD and MAD processes over a period of 70 weeks.
Figure 12: Biogas Methane composition data obtained THAD and MAD processes (3 replicates of THAD and a control - CMAD).

The biogas composition was on average, 64% CH₄ in the MAD control digester and 65 % CH₄ in the THAD and they all showed a stable digestion over the period of the project. The data obtained shows that the thermophilic digestion process used was as robust as mesophilic digestion process.

Biogas Carbon dioxide composition

Figure 13 shows the biogas carbon dioxide composition produced from THAD and MAD processes.

Figure 13: Biogas Carbon dioxide composition data obtained from the anaerobic digestion types investigated

The biogas composition was on average 35% and 34% CH₄ in THAD and MAD processes and they all showed a stable digestion over the periods monitored.

The biogas composition surprisingly showed normal methane and carbon dioxide content of biogas over the experimental periods even during times of instable digestion process shown by reduced biogas volume (fig 10), VFA build up (fig 5) and depletion of Alkalinity concentration (fig 6).
Therefore, the stability of anaerobic digestion process should always be measured in conjunction with biogas volume produced. Consequently, this work shows that the pH data should be used in conjunction with VFA and alkalinity, the biogas composition should be used conjunction with biogas volume produced as stand-alone data from each could be misleading.

Final product pathogen contents

Table 1 summarises the extent of indicator pathogen kill achieved in THAD and MAD processes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hydrolysed feed</th>
<th>CMAD - THP</th>
<th>THAD 1</th>
<th>THAD 2</th>
<th>THAD 3</th>
<th>THADs Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ecoli removal/kill (log)</td>
<td>&lt;2.18</td>
<td>&lt;2.40</td>
<td>&lt;2.39</td>
<td>&lt;2.40</td>
<td>&lt;2.40</td>
<td>&lt;2.40</td>
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As expected, the data shows that both the THP pre-treated feed and the digestion processes employed achieved total indicator pathogen kill; 6-log reduction of indicator organisms (Shana et al, 2016).

Sludge dewatering ability

Cake dry solids content

Figure 14 shows the digested and dewatered sludge cake dry solids data using a laboratory piston press method from the THAD and MAD processes monitoring period of 70 weeks.

The average cake dry solid contents from THAD was 30.3% and that of the control MAD was 28.4% indicating some degree of improvement on the sludge dewaterability (Shana et al, 2016). However, during a period of digestion process instability, the digested sludge obtained from the THAD process...
showed significantly reduced cake dry solids content, between 28 and 29%, but not deteriorating below the data obtained from the control MAD.

**Polymer dose rate**

Figure 15 shows polymer dosing rate used during THAD and MAD digested sludge dewatering process. As expected the data showed higher polymer usage in the THAD digested sludge than conventional MAD digested.

![Polymer dose rate consumed during THAD and MAD digested sludge dewatering process](image)

**Figure 15:** Polymer dose rate consumed during THAD and MAD digested sludge dewatering process investigated

The data in Figure 15 shows the average polymer dose rate found in dewatering of THAD and MAD digested sludge were 11.40 and 10.0 kg/TDS, respectively. In this case, the data shows that THAD digested sludge consumed higher polymer dose than that of MAD digested sludge. However, between weeks 1 to 32 the polymer dose rate used in the THAD digested sludge is within expected range and the slight improvement seen in cake dry solids compensated for the slightly higher polymer consumption in the THAD process. Further deterioration in THAD digested sludge polymer consumption was observed due to operational issue experienced between weeks of 46 and 65. The cause of enhanced polymer consumption was attributable to the high amount of VFA residue present in the digested sludge from week 50 onwards (fig 5).

**Conclusions**

Overall, thermophilic anaerobic digestion of THP hydrolysed sludge at thermophilic temperature range of 46°C, 47°C, 48°C, 49°C, 50°C, 52°C, 53°C, 54°C, 55°C and 56°C performed as well as the conventional THP hydrolysed sludge operating under conventional MAD process at 42°C. Contrary to previously reported process instability of THAD, this work shows that there was no biology process related performance inhibition or deterioration in anaerobic digestion performance at lower and higher thermophilic temperature ranges.

Overall, the process proved to be stable at HRT of 13.3 - 16 days and l temperature fluctuation of between 1 – 2 °C did not significantly impact the digester performance.
Digester loading of 4 – 5 kg VS m$^{-3}$ day$^{-1}$ was achievable during the thermophilic digestion of THP-treated sludge in terms of enhanced VSr and biogas production. The biogas quality was also stable over the monitoring period.

Although, the lab-scale thermophilic digestion of THP-treated sludge showed improved gas production and sludge cake dry solids content, larger pilot-scale operational time is required to prove the impact of thermally hydrolysed sludge on THAD performance and its retrofitting in the THP system.

Installation of more THP process to pre-treat sludge feed has resulted in the availability of significant amount of low grade heat which has to be removed during conventional MAD process in order to ensure the effective operation. Significant savings could be made if there were no requirements to remove this heat through operation of the THP +THAD configuration.

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