COMPARISON OF THE PERFORMANCE OF ANAEROBIC DIGESTION OF THERMALLY HYDROLYSED SLUDGE DURING THEROMOPHILIC AND MESOPHILIC ANAEROBIC DIGESTION

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Abstract

Thermophilic anaerobic digestion process is predominantly used as a pre-treatment process based on a shorter Hydraulic retention time (HRT) in USA, Germany and elsewhere mainly to pasteurise sludge. Standalone longer HRT thermophilic digestion process has also been used at the lower end of the thermophilic temperature range but due to increased heat requirements of the process, its use has been limited. Recently, the use of Thermal Hydrolysis Process (THP) to pre-treat digester feed has significantly increased resulting in the availability of significant amount of low grade heat which has to be removed before to ensure effective operation of Mesophilic Anaerobic Digestion (MAD). In this paper, the performance of thermophilic AD of THP pre-treated sludge was investigated in comparison with THP+MAD.

The results obtained from laboratory scale experiments showed that the thermophilic anaerobic digestion process achieved an overall average VSr range of 50 - 66% in comparison with the mesophilic anaerobic digestion process which provided a VSr range of 48- 54%. As a result, the overall biogas production from the thermophilic anaerobic digestion process was found to be in excess of 420 m3/tonne dry solids (TDS) fed, compared with 409 m3/tds feed from mesophilic anaerobic digestion process.

Keywords

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

Introduction

Anaerobic digestion is one of the oldest wastewater treatment process unit operations and is an essential tool for protecting the environment and public health. It is a well-known fact, that the anaerobic digestion process converts potential pollutant organic substrates to economically useful by-products such as biogas and digestate. It also offers public health (sanitation) benefit by eliminating odour, killing pathogens and preventing the spread of diseases.

Anaerobic digestion processes are classified into three types based on the digestion temperature ranges used. These are known as psychrophilic, mesophilic and thermophilic digestion temperature ranges. The psychrophilic temperature ranges from 0 - 25^{o}C, mesophilic from 25 - 45^{o}C and thermophilic from 45 - 70^{o}C (Shamskhorzani and McKinney, 1990; Aoki and Kawase, 1991 cited in Aitken and Mullennix, 1992; and Shana, 2015). Psychrophilic digestion (cold digestion) takes place when sludge is intentionally stored in storage tanks or when unintentionally stored in primary settlement tanks.

According to Ziganshin *et al.* (2013) cited in Moset *et al*. (2015), temperature and substrate composition are amongst the main factors that affect the performance of anaerobic digestion process. However, no consensus exists on the temperature ranges where effective substrate anaerobic digestion takes place (Moset *et al*., 2015).

The optimum digestion temperature for mesophilic anaerobic digestion ranges 38 - 45 ^{o}C. However, often used optimum mesophilic digestion temperature aimed at pathogen kill is in the range 35± 2^{o}C. Currently, in the UK, the industry-wide optimum mesophilic anaerobic digestion temperature range used for an enhanced biogas production and pathogen kill is 38 -45 ^{o}C.

The optimum thermophilic anaerobic digestion temperature ranges is reported to be between 55 - 60^{o}C. This temperature range is often used for sludge pasteurisation. Earlier studies of thermophilic anaerobic digestion reported that the temperature ranging of 45 - 54 ^{o}C could be problematic and therefore to be avoided (Fair and Moore, 1934; Hills and Schroeder, 1969 cited in Kardos *et al*., 2011). They hinted that above 42^{o}C, the overall anaerobic digestion performance including biogas production is significantly reduced.

In addition, other authors further claimed that biogas production was significantly reduced when thermophilic digestion was run above 60^{o}C (Malina and Pohland, 1992) and ceasing above 70 ^{o}C (Kardos *et al*. 2009). Therefore, the above claims coupled with increased power and energy costs, affected the economics of the thermophilic anaerobic digestion process.

However, a stable performance of thermophilic anaerobic sludge digestion process has been reported in the USA (Garber, 1982), Germany (Oles *et al*., 1997) and a number of other European countries. Garber (1982) investigated anaerobic digestion of sewage sludge in the thermophilic temperature range and stated that the process had been very stable and performed as well as mesophilic digestion process in full scale plant in the Hyperion WWTP of the City of Loss Angeles.

It has also been reported that thermophilic digestion is very sensitive to sudden changes in temperature more than mesophilic digestion (Buhr and Andrews, 1977). However the results reported in the literature are still contradictory on this issue. Buhr and Andrews also stated that in their studies Fisher and Greene (1945) noted that a rise or drop of 3 ^{o}C or more during a relatively short period of time greatly affected the thermophilic process and could cause a temporary complete cessation in digestion activity whilst Garber (1954) reported that the thermophilic process was quite stable and resistant to upset with temperature drops of 5^{o}C in 48 h producing no unusual changes.

The temperature fluctuation tolerated by mesophilic systems is 3 – 5 degC, whereas the temperature fluctuation tolerated by thermophilic system is 1 – 2 degC (Kardos *et al*., 2011). These authors reported the VFA concentration of 1500 – 2500 mg/l and 3000 -4000 mg/l in mesophilic and thermophilic digestion processes respectively.

In terms of performance, Hashimato *et al* (1981) and Palatsi *et al* (2009) both cited in Moset *et al*. (2015) , tested a range of temperatures using cattle manure and mixture of wastewater primary and secondary sludges and did not find a significant difference between the thermophilic and mesophilic digesters in terms of overall digestion process performance.

Sung and Liu (2003) reported that ammonia nitrogen concentration increased in mesophilic or thermophilic digesters as a result of the urea and protein hydrolysis. However, this author stated that no clear differences were observed in ammonia concentration between mesophilic and thermophilic temperature ranges investigated. According to Labatut and Gooch (2012), ammonia is produced during the digestion of protein-rich substrates, such as swine or cow manure. Likewise VFAs, ammonia can inhibit the digestion process and decrease its overall performance. Concentrations over 1,500 mg/L of ammonia-N have been reported to be inhibitory for the digestion process at high pH (i.e., > 7.4); however, acclimation to higher ammonia levels (>5,000 mg/L) has been also reported in manure systems.

Thermophilic anaerobic digestion is often used as sludge pre-treatment as a part of dual digestion where the combined impact in terms of digestion process stability, volatile solid reduction efficiency, pathogen kill efficiency and sludge dewatering ability was achieved. The first stage thermophilic anaerobic process is run at shorter HRT in the range of 1 – 3 days, while the second stage mesophilic is operated at HRT in the range of 12 – 15 days (Lu and Ahring, 2007).

Since late 1990s, more advanced sludge digestion processes, particularly thermal hydrolysis process (THP) has been utilised in the UK, but standalone thermophilic digestion process is rarely used.

The main objective of this investigation was to compare the performance of two THP pre-treated lab-scale digestion systems operating in the thermophilic and mesophilic temperatures. The detailed objectives of this study were:

- To determine if the performance of thermophilic anaerobic digestion process fed with thermally hydrolysed sludge and run at temperature ranges of 45 ^{o}C, 46 ^{o}C, 47^{o}C, 48 ^{o}C, 49 ^{o}C and 50 ^{o}C are as stable as the mesophilic digestion process run at 42 ^{o}C
- To quantify the gas production capabilities of THP- fed thermophilic digestion process in comparison with MAD
- To assess the dewaterability of the resulting sludges

Materials and methods

Substrate Source

The THP treated sludge feed was collected on daily bases from Thames Water’s Crossness STWs consisting of 60% primary sludge and 40% SAS on dry weight basis. On average, the digester feed consisted of 7.5% dry solids and 84.7% volatile solids content.

Experimental Set-up

The lab-scale digestion rig used consisted of 3 replicate digesters used as “treatment” and a single digester used as a control. The digesters used were 10L each with effective digester volume and 8L working volume. The digester feeding regime was hydraulically controlled.

The treatment digesters were initially heated in a water bath at 46 ± 0.3^{o}C and the control digester was similarly heated in a separate water bath at 42 ± 0.3^{o}C. After 3HRTs the digester temperature for the treatment digesters was changed by 1 ^{o}C and while keeping the control digester at constant temperature at 42 ± 0.3^{o}C. The digestion temperature was raised to 50 ± 0.3^{o}C each time raising the temperature by one degree allowing a minimum of 3HRTs in each step. The digesters were continuously stirred (excluding during digester feeding time) using paddle stirrers driven by geared motor at 118 – 120 rpm. Gas was collected via gas outlet tube connected to 10 litre aspirator bottles by water displacement. The digesters were fed once daily at regular intervals with a pre-determined feed volume.

Characterisations of sludge chemical and physical properties

The digester feed and digested sludge samples were analysed for dry solids, volatile matter and volatile fatty acids (VFA) at least twice a week. Sludge ammonical nitrogen concentration was also analysed on weekly basis. Sludge indicator pathogen was checked for each digestion temperature tested and sludge dewaterability was carried out once per digestion temperature. Sludge samples were taken and analysed as per Standard Methods for the Examination of Water and Wastewater (APHA, 1998).

Results and discussion

Table 1 shows the average digestion process performance data during 27 weeks of thermophilic anaerobic digestion of THP pre-treated sludge at 46 – 50ºC compared with the control mesophilic digestion which was also fed with THP pre-treated sludge.

Table 1: Summary performance indicator parameters for anaerobic digestion types investigated (average ± standard deviation); N= 27

Parameter	Feed	MAD at 42ºC	THAD at 46ºC	THAD at 47ºC	THAD at 48ºC	THAD at 49ºC	THAD at 50ºC
pH	5.5±0.2	7.9±0.1	7.8±0.1	7.9±0.1	8±0.04	8±0.11	8.1±0.1
VFA (mg/l)	2643±690	294±325	763±555	306±68	309±50	304±88	849±755
Alkalinity (mg/l)	2703±155	9173±555	8446±1051	9558±354	10220±295	10012±332	9832±299
VFA to alkalinity ratio	0.97±0.22	0.03±0.04	0.09±0.07	0.03±0.01	0.03±0.01	0.03±0.01	0.09±0.08
HRT (days)	-	13	13	13	13	13	13
VS loading rate (kg/m3 day)	-	4.6±0.1	3.9±0.2	4.1±0.5	4.8±0.1	4.6±0.05	4.5±0.1
VS destruction (%)	-	50.6±2.3	66.2±7.9	55.5±2.7	49.6±2.7	45.5±1.9	50.7±2.4
Biogas yield (m3/TDS fed)	-	409±37	405±93	465±37	427±5	423±18	400±30
Specific biogas production (m3/kg VS destroyed).	-	0.8±0.1	0.6±0.2	0.8±0.05	0.9±0.01	0.9±0.04	0.8±0.08
Methane composition (%)	-	63	65	64	65	65	65

Carbon dioxide composition (%)	-	35	35	35	35	35	35

Hydraulic retention time (HRT days)

Figure 1 shows 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 47ºC while keeping the temperature of MAD control digester constant at 42ºC.

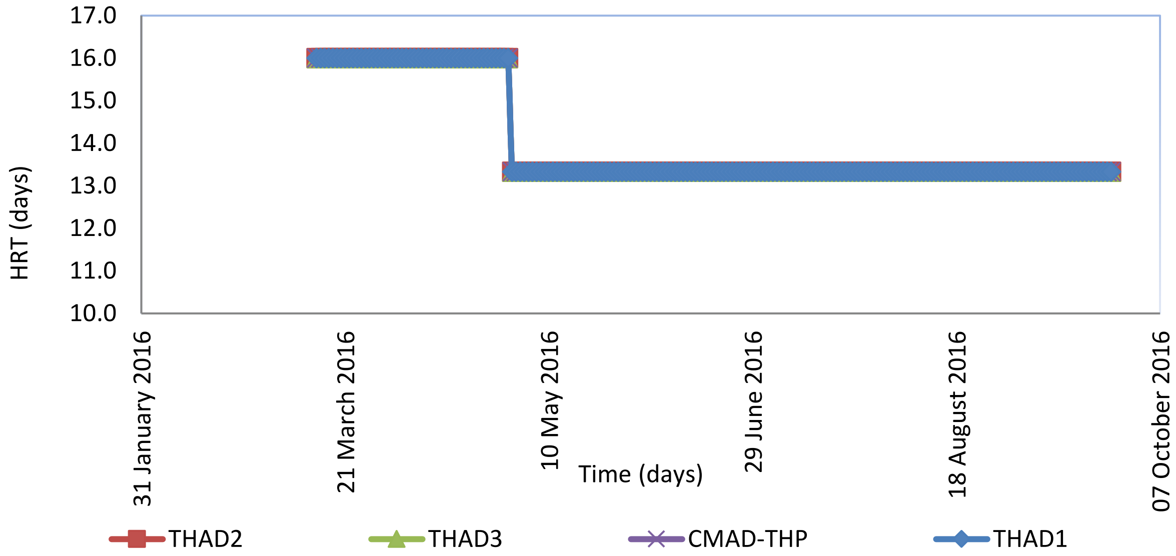


Figure 1: Hydraulic retention time in days in the anaerobic digestion types investigated

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 manged if HRT is properly controlled and used; HRT determines a correct and stable food to biomass ratio. 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).

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.

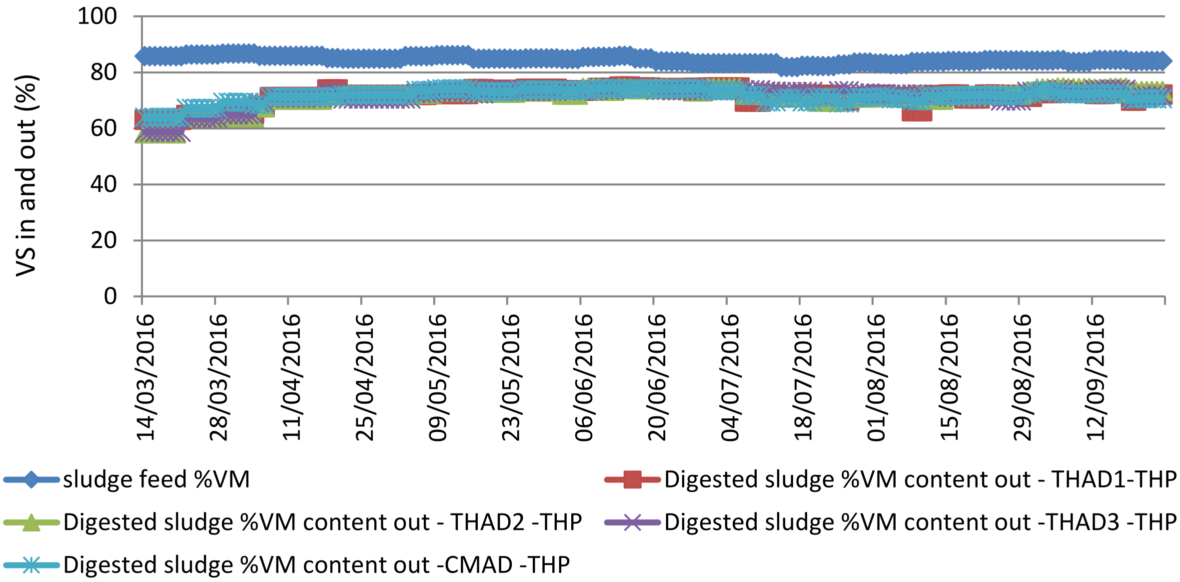


Figure 2: Volatile solids input and output monitored during the anaerobic digestion types investigation

The data in Figure 2 shows that the THP hydrolysed sludge feed volatile solids ranged from 84 – 85%. Figure 2 also shows the digested sludge volatile solids content ranging from 72 – 73%. This is 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). Regular monitoring of digester input and output digester feed volatile solids can inform experienced operators and researchers how stable the digestion process is.

Volatile solids loading rate

Figure 3 shows the digester volatile solids loading rate (VSLR) in the THAD and MAD processes. 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.

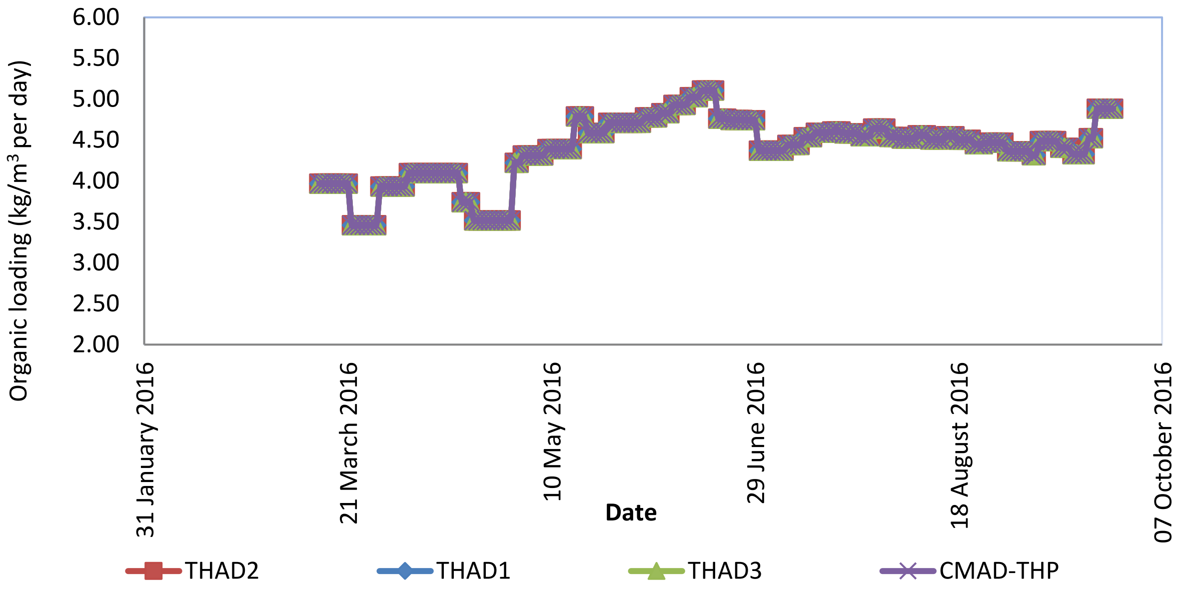


Figure 3: Volatile solids loading rate used in the anaerobic digestion types investigated

Thermophilic and control MAD digesters were operated on a volatile solids load rates ranging between 3.6 and 4.9 kg VS $m^{-3}day^{-1}$. Average volatile solids load rate for THAD was 4.6 kg VS $m^{-3}day^{-1}$ and that of MAD digestion was 4.6 kg VS $m^{-3}day^{-1}$. These results indicated that both digesters showed a stable digestion processes at low as well high VSLR were used. Therefore, there is an added value to be gained if THP hydrolysed sludge was to be fed to THAD in terms of avoiding time wasted for cooling the hydrolysed sludge temperature in meeting the mesophilic digestion temperature requirement.

Volatile solid destruction

Figure 4 shows the sludge volatile solid reduction (VSr) during THAD and MAD temperature ranges investigated.

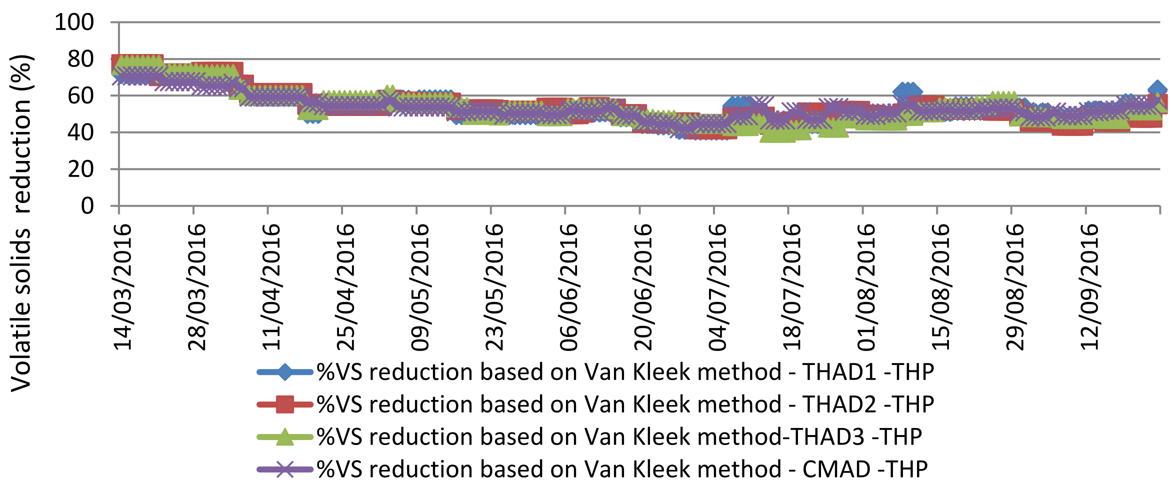


Figure 4: Volatile solids reduction during THAD and MAD anaerobic digestion process

The VSr in the THAD process ranged from 50 -66% whereas in the MAD process it ranged from 48 – 54%. The overall VSr in the THAD process shows the potential benefit of 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 reduced during THAD and MAD anaerobic digestion processes.

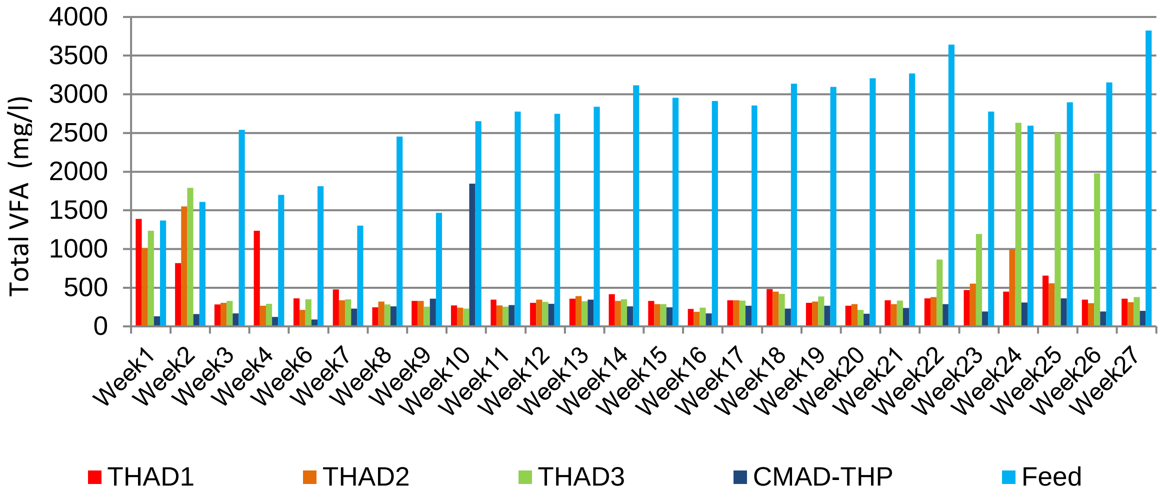


Figure 5: Volatile fatty Acid content monitored in the sludge feed and anaerobic digestion types investigated

The VFA content of MAD digested sludge averaged 293 mg/l, whereas that of THAD ranged from 304 - 849 mg/l (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 (2015) showed that the VFA content of thermally hydrolysed and digested sludge often produced about 2 – 2.6 times more VFA concentration than that of conventional MAD process. The VFA results found from this THP hydrolysed sludge thermophilic digestion work concurred with the findings of Shana (2015) and showed a stable anaerobic digestion process in all the digestion temperatures investigated.

Alkalinity production

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

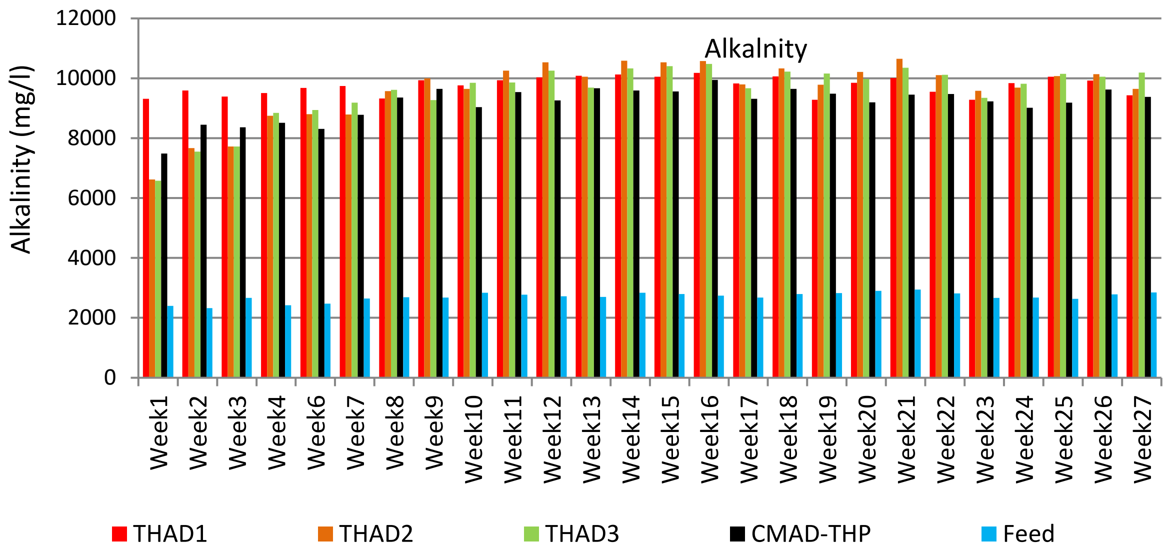


Figure 6: Alkalinity content monitored in the sludge feed, THAD and MAD processes

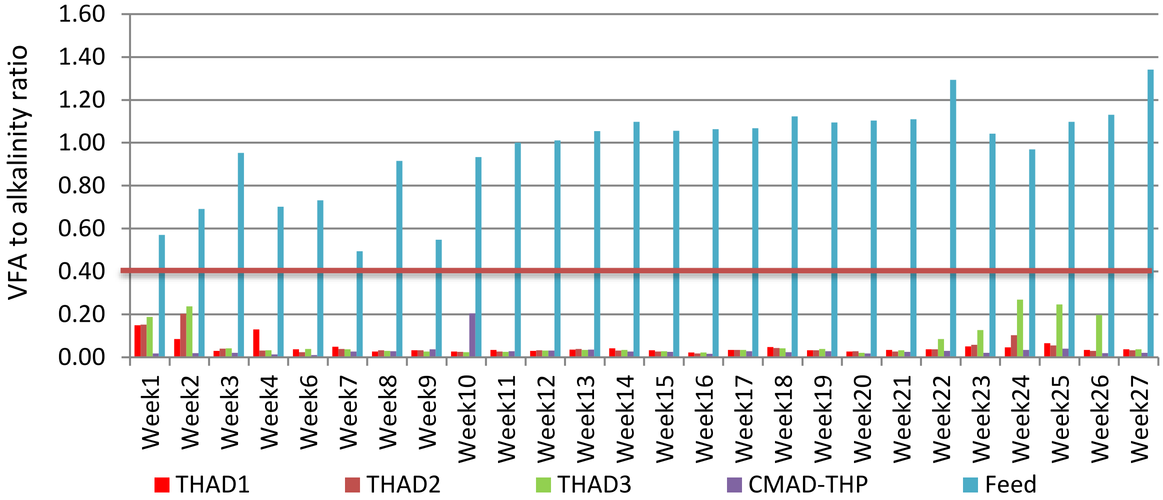
The alkalinity increased by 3.1 - 3.7 times in different thermophilic digestion temperature ranges investigated when compared to the alkalinity content of the digester feed. Similarly 3.4 fold increases in the MAD digested sludge alkalinity content was observed when compared with the alkalinity content of thermally hydrolysed sludge feed.

The average alkalinity data found in the digested sludge at temperatures of 42^{o}C, 46^{o}C, 47^{o}C, 48^{o}C, 49^{o}C and 50^{o}C were 2,703, 9,173, 8,446, 9,558, 10, 220, 10,012 and 9,832 mg/l, respectively. These high digesting sludge alkalinity and relatively high residual VFA content in the digesting sludge often gives a balanced environment in the digester for effective methanogenic bacteria activity, therefore the balance of these to two digestion process parameters is very important for maintaining a stable anaerobic digestion process condition.

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.

Figure 7: VFA to Alkalinity ratio monitored in the sludge feed and anaerobic digestion types investigated (red line shows VFA to alkalinity threshold value)



The VFA to alkalinity ratio is an important tool for anaerobic digestion process management and shows how well accommodating the digester environment to methanogenic bacteria is. It is an acknowledged fact that when the VFA to alkalinity ratio exceeds 0.4, the anaerobic digestion process is considered as deteriorating.

The data in Figure 7 shows the VFA to alkalinity ratio of 0.03, 0.09, 0.03, 0.03, 0.03 and 0.09 in the anaerobic digesters operated at all the temperatures of interest indicative of stable anaerobic digestion process. The VFA to alkalinity ratio in the feed sludge was 0.97 indicating a significant amount of volatile acids in the feed.

pH

Figure 8 shows pH of the THP pre-treated feed, THAD and MAD digested sludges.

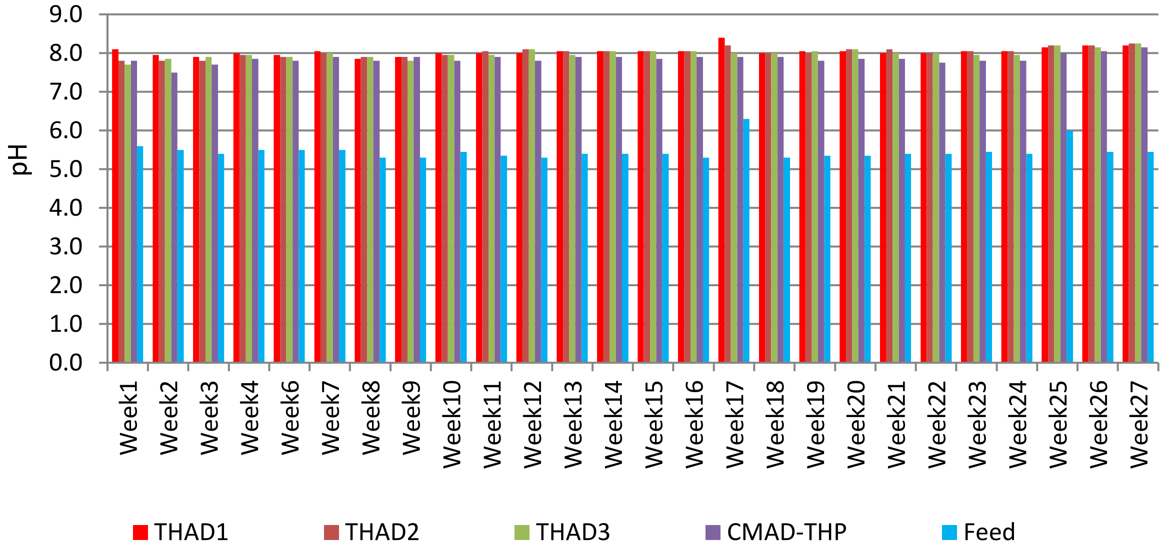


Figure 8: pH monitored in the sludge feed and anaerobic digestion types investigated

The sludge feed and digested sludge pH measured shows the extent of interaction between sludge VFA and alkalinity content. Higher VFA and lower alkalinity causes reduced pH and vice versa. The data in Figure 8 and Table 1 show stable Thermophilic and mesophilic digestion processes. The pH of all the anaerobic digestion run at 42ºC, 46ºC, 47ºC, 48ºC, 49ºC and 50ºC had an average pH of 7.9, 7.8, 7.9, 8, 8, and 8.1 respectively. The data obtained are very similar to pH values obtained from THP hydrolysed and MAD processed sludges reported by Shana (2015).

Digester Ammonical Nitrogen content

Figure 9 shows the ammonical nitrogen concentration in the THAD and MAD digested sludges.

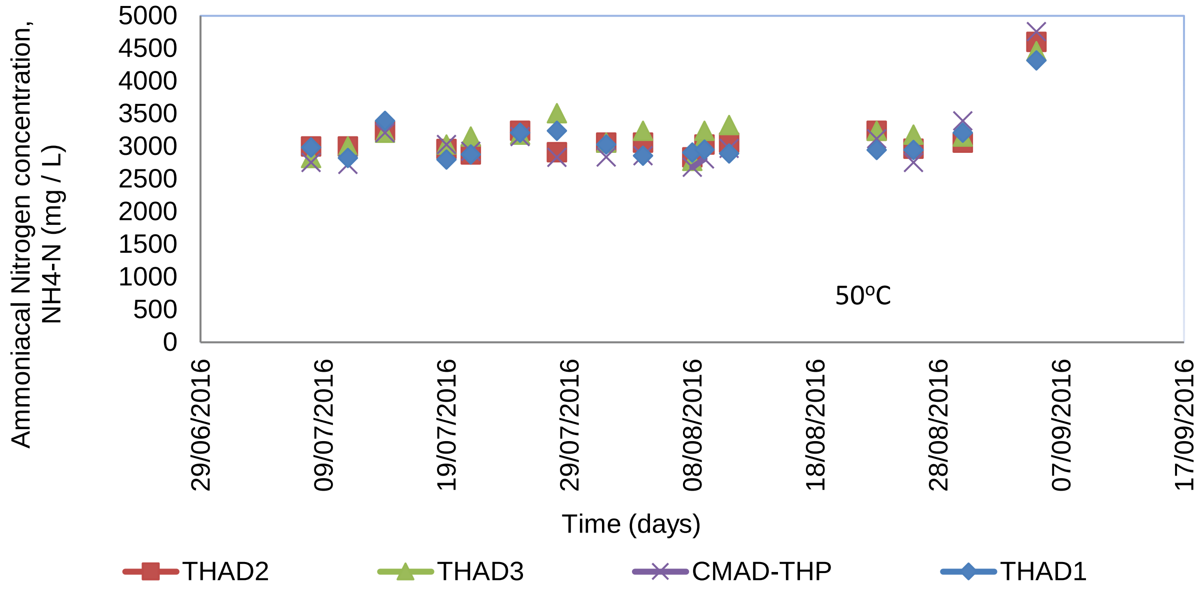


Figure 9: Ammonical Nitrogen content in 3 replicates THAD and control MAD sludges

The data obtained from this work showed elevated ammonical nitrogen concentration in all the digestion temperatures investigated, however, no detrimental effect to methanogenic bacteria was observed in all the digestion as indicated by stable biogas production regardless of the digester temperatures investigated.

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 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 to the determent of the overall anaerobic digestion process due early corrective measures.

The data obtained in this work was similar to the data reported by Sung and Liu (2003), where an increase of ammonical nitrogen concentration in both thermophilic and mesophilic digestion was observed.

Gas production

In this work the biogas production in the thermophilic and mesophilic digestion processes was measured in terms of biogas yield and specific biogas production.

Biogas yield

Figure 10 shows the biogas yield obtained from the thermophilic and mesophilic digestion of thermally hydrolysed sludge.

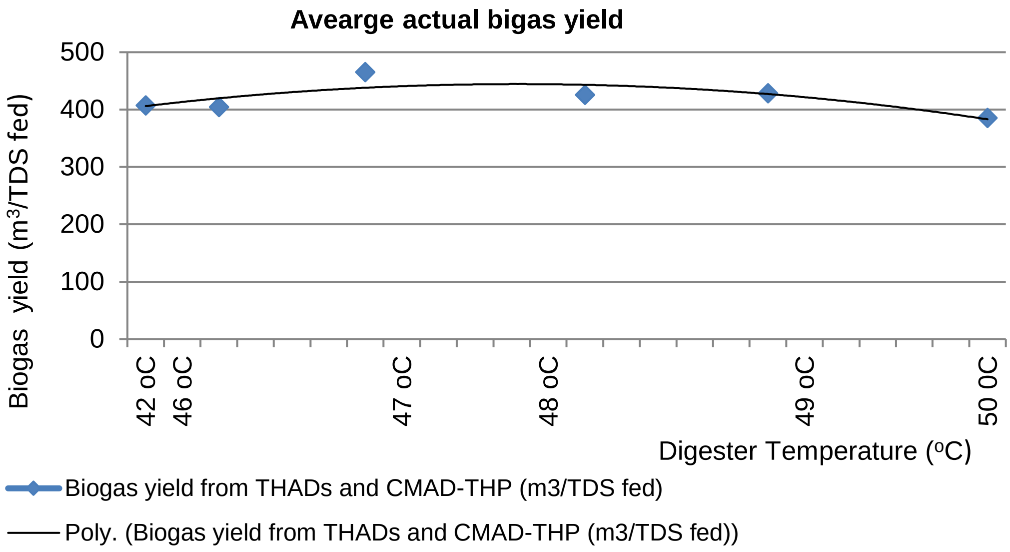


Figure 10: Biogas yield obtained from THAD and MAD processes

The data in Figure 10 shows the anaerobic digestion processes temperatures of 42ºC, 46ºC, 47ºC, 48ºC, 49ºC and 50ºC and corresponding average biogas yield of 409, 405, 465, 427, 423 and 400 m3/TDS fed respectively. The thermophilic digestion at 47ºC 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.

The data obtained from this work is in agreement with Hashimato and colleagues (1981) and Palatsi and colleagues (2009) who tested a range of temperatures on cattle manure and mixture of primary and SAS obtained from wastewater treatment processes and they 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.

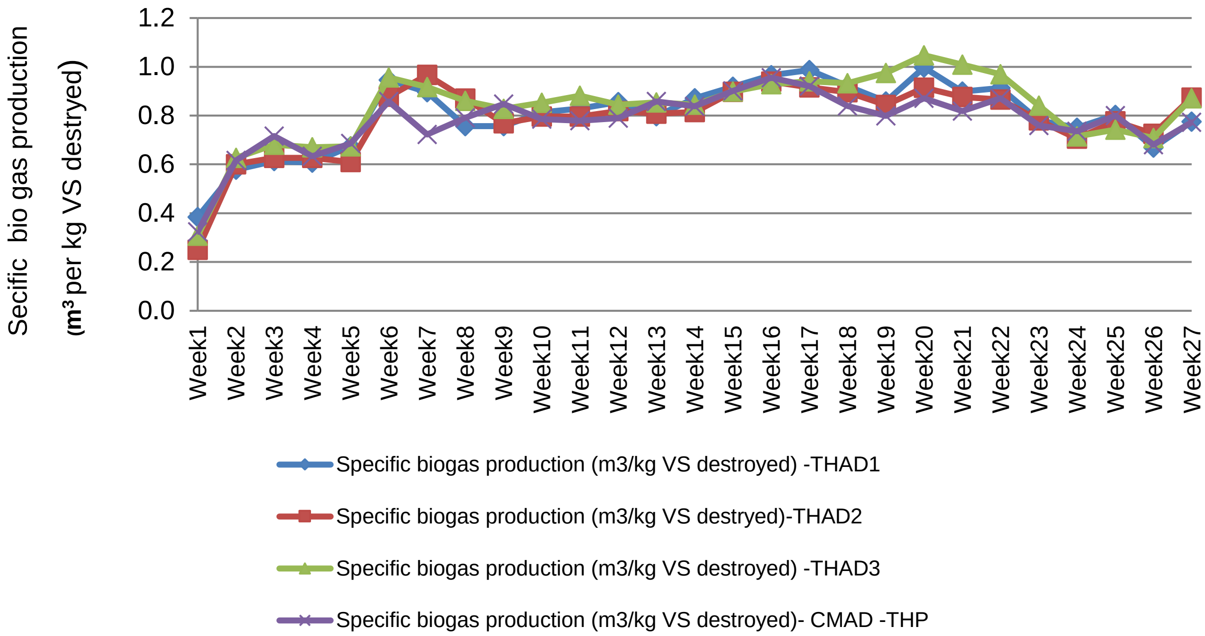


Figure 11: Specific biogas production data obtained from the anaerobic digestion types investigated

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

The data also shows that the thermophilic digestion processes performed as well as the mesophilic 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 0.9-1m³/kg VS destroyed. Therefore, it is recommended to use specific site values than 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

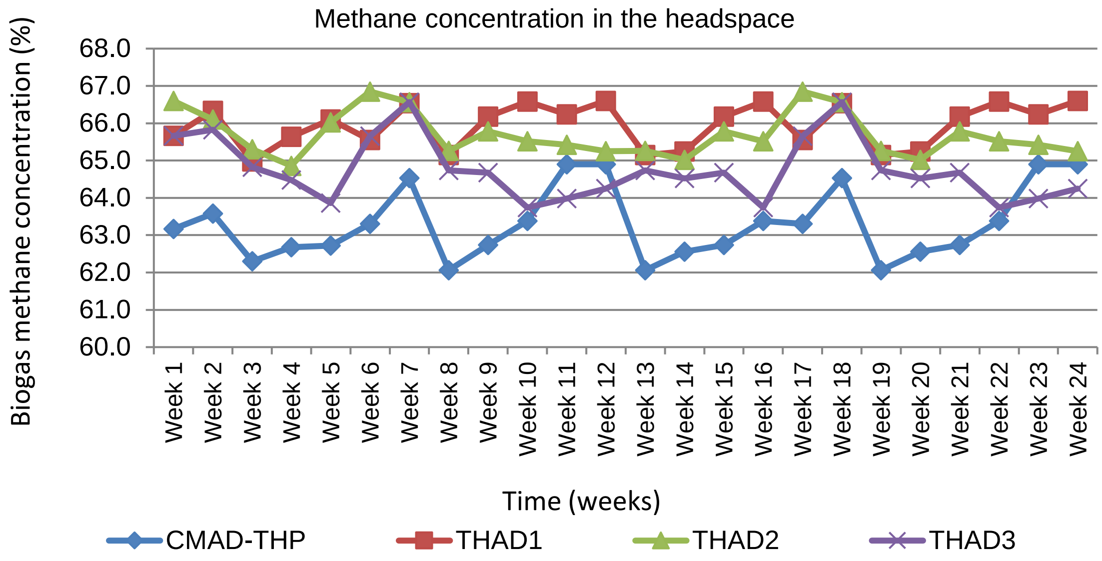


Figure 12: Biogas Methane composition data obtained THAD and MAD processes (3 replicates of THAD and a control- CMAD).

The biogas composition was, on average, 63% CH_4 in the MAD control digester and 65 % CH_4 in the thermophilic digesters and they all showed 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

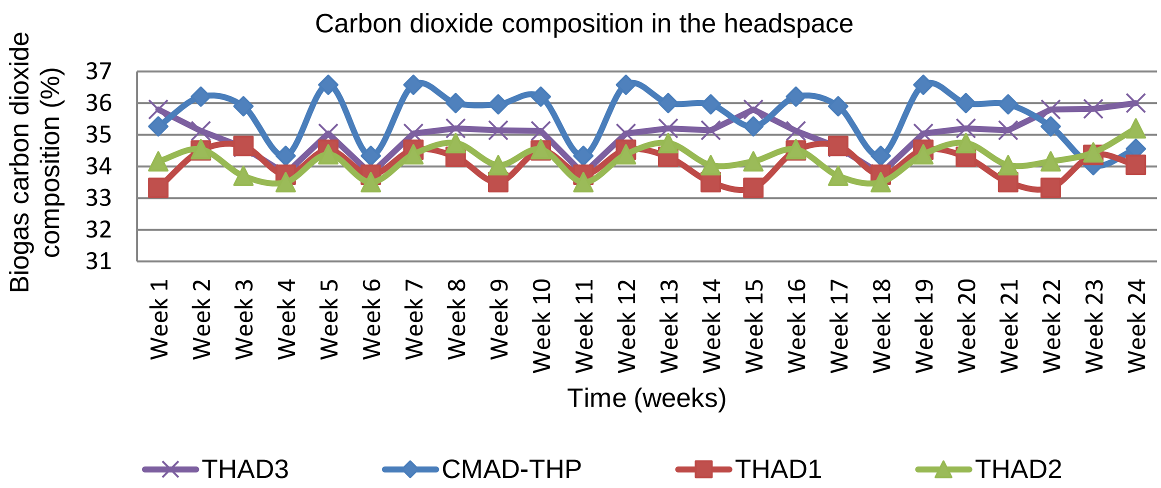


Figure 13: Biogas Carbon dioxide composition data obtained from the anaerobic digestion types investigated

The biogas composition was on average 35% CH_4 in both the MAD control digester in the thermophilic digesters and they all showed stable digestion over the period of the research work.

Final product pathogen contents

Table 2 summarises the extent of indicator pathogen kill achieved in THAD and MAD processes.

Table 2: Ecoli removal/kill in hydrolysed sludge feed and digested sludge types assessed

Parameter	Hydrolysed feed	CMAD - THP	THAD 1	THAD2	THAD3	THADs Average
Ecoli removal/kill (log)	<2.18	<2.41	<2.36	<2.42	<2.41	<2.40

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.

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.

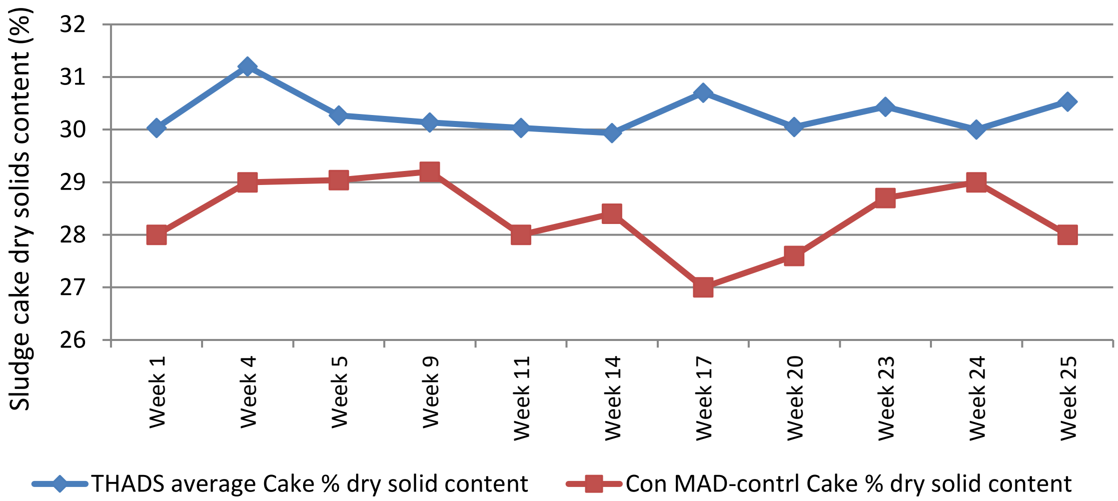


Figure 14: Digested and dewatered sludge cake dry solids data obtained from THAD and MAD processes investigated

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. This may be due to higher disintegration of cell walls of bacterial biomass therefore, creating smaller particle sizes and releasing more of bound water.

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.

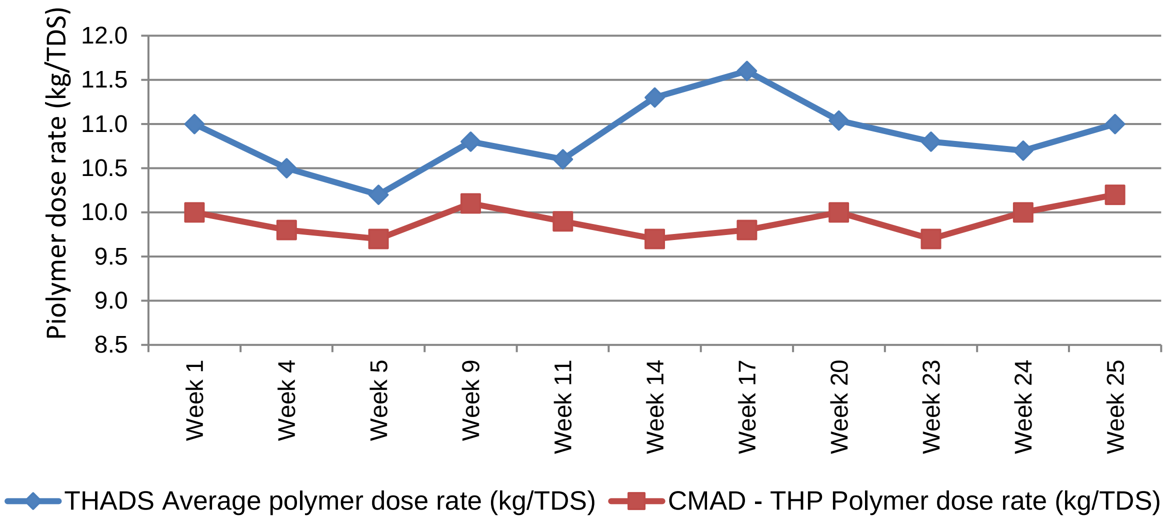


Figure 15: Polymer dose rate consumed during THAD and MAD digested sludge dewatering process investigated

The data in Figure 15 shows the average polymer dose rate found in dewatering digested sludge obtained from THAD and MAD processes were 10.87 and 9.9 kg/TDS, respectively. In this case, the data shows that thermophilic digested sludge consumed required higher polymer dose than mesophilic digested sludge. However, 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.

Conclusions

Overall, thermophilic anaerobic digestion of THP hydrolysed sludge digestion at lower thermophilic temperature range of 46ºC, 47ºC, 48ºC, 49ºC and 50ºC performed as well as the conventional THP hydrolysed sludge MAD process run at 42ºC. Contrary to previously reported issues with temperature instability of THAD, no performance inhibition or deterioration was observed at these temperatures.

Overall digestion process proved to be stable at HRT of 13.3 - 16 days and temporary temperature fluctuation did not significantly impact the digestion process performance.

Digester loading of 4 – 4.6 kg VS m^{-3} day^{-1} was acceptable for successful performance of thermophilic digestion of thermally hydrolysed 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 thermally hydrolysed sludge showed improved gas production and sludge cake dry solids, longer pilot-scale operational time is required to prove the impact of thermally hydrolysed sludge on THAD performance and its retrofitting in the THP system.

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