A TALE OF TWO SLUDGES – TRIALLING OPERATIONAL TEMPERATURE CONTROL OF ANAEROBIC DIGESTER

Jamie Roverts, Becky Macdonald, Sarah Burgess (CH2M Beca) and Lee Liaw (Christchurch City Council)

ABSTRACT

It was the best of slimes, it was the worst of slimes…

Anaerobic digestion is a commonly used method of solids stabilization in municipal wastewater treatment plants. The Christchurch Wastewater Treatment Plant (CWTP), owned by Christchurch City Council (CCC), operates a Temperature-Phased Anaerobic Digestion (TPAD) system, wherein primary sludge and secondary sludge are combined and then digested in a 55°C thermophilic stage followed by a 35°C mesophilic stage.

This paper describes a trial investigating diverting cold secondary sludge directly to the mesophilic digesters to provide cooling. The full scale trial was conducted on a single mesophilic digester (Digester 4), to determine the viability of this approach before full implementation. The trial involved monitoring the performance of Digester 4 to assess whether the change in feedstock negatively impacted digestion or downstream processes. Parameters monitored to assess performance included: biogas production, methane concentration, hydrogen sulfide concentration, volatile and total solids, pH, and various volatile acids.

The trial results show that supplementary cooling of the mesophilic digesters using secondary sludge did not negatively affect the performance of Digester 4. A general increase in the rate of volatile solids destruction from 17% up to 30 – 45% was observed for Digester 4, indicating that the microbial population responded positively to the adjusted feedstock.

Planning is now underway to convert all four mesophilic digesters over to secondary sludge cooling. As a result, the aging spiral heat exchangers will not be replaced providing a CAPEX saving in the order of $1 million and increased on-site bore water availability.

KEYWORDS

Anaerobic digestion, operations

1 INTRODUCTION

1.1 BACKGROUND

The Christchurch Wastewater Treatment Plant (CWTP) uses a temperature phased anaerobic digestion (TPAD) process to treat sludge produced by the main process stream. Raw sludge from the primary and secondary stages of the treatment plant is blended and fed to the thermophilic stage in Digesters 5 and 6 (which operates at approx. 55°C), followed by mesophilic digestion in Digesters 1 to 4 (operated at approx. 35°C) . To reduce the temperature of sludge exiting the thermophilic stage at ~55°C, it is cooled to approximately 43°C using the incoming cold, raw sludge. Additional cooling is required to reduce the temperature of the sludge to 35°C for mesophilic digestion. See Figure 2 for an indicative PFD of the digestion system operated by CWTP.

This additional cooling is currently provided by adapting the Digesters 1 – 4 existing spiral heat exchangers, and cooling site bore water (C2 water) as a single-pass cooling fluid. These heat exchangers were originally designed to heat sludge, with heat coming from the site's closed-loop hot water system, which was treated to prevent corrosion. The C2 water is untreated and there is evidence that the heat exchangers are corroding as a result. The volume of C2 water required to cool the sludge is also constraining process water availability for other site users, as C2 water is supplied from two dedicated bores on site which have consented maximum daily extraction volumes. Operating the spiral heat exchangers at colder temperatures has also increased the rate of struvite deposition in the sludge-side channels, reducing the transfer efficiency of the exchangers. Hence a robust and resilient long term solution is required.

This paper describes a trial undertaken to explore the feasibility of using secondary sludge to cool the mesophilic digesters. The challenges of planning and implementing the trial are discussed. The extensive sampling programme is described and the results are presented. The challenges of undertaking a full scale trial on an operating wastewater treatment plant are also discussed.

1.2 ANAEROBIC DIGESTION

Throughout this assessment, reference will be made to the various stages of anaerobic digestion, of which there are four generally accepted steps (Lu & Ahring, 2007), see Figure 1.

- Step one comprises the breakdown of organic polymers such as carbohydrates, proteins and lipids fed to the digestion process. These polymers undergo hydrolysis, instigated by extracellular enzymes, and are converted to soluble organics (glucose, amino acids and fatty acids).

- During step two, these species are processed by acidogens to produce organic acids (acetic acid and propionic acid) as well as hydrogen, carbon dioxide and acetate.

- In step three the remaining organic acids are converted by acitogens to carbon dioxide, hydrogen and acetate.

- During step four the organic acids and hydrogen undergo methanogenesis to yield methane and carbon dioxide, effectively completing the digestion process.

Anaerobic digestion is a complicated process reliant on synergy between different microorganisms to act together as a microbial consortia. The various processes the microorganisms participate in must be balanced to promote effective digestion. As such, the overall digestion process is heavily dependent on environmental factors such as pH, temperature, the presence of inhibitory or toxic substances, and operational factors such as solids retention time, organic loading rate and mixing.

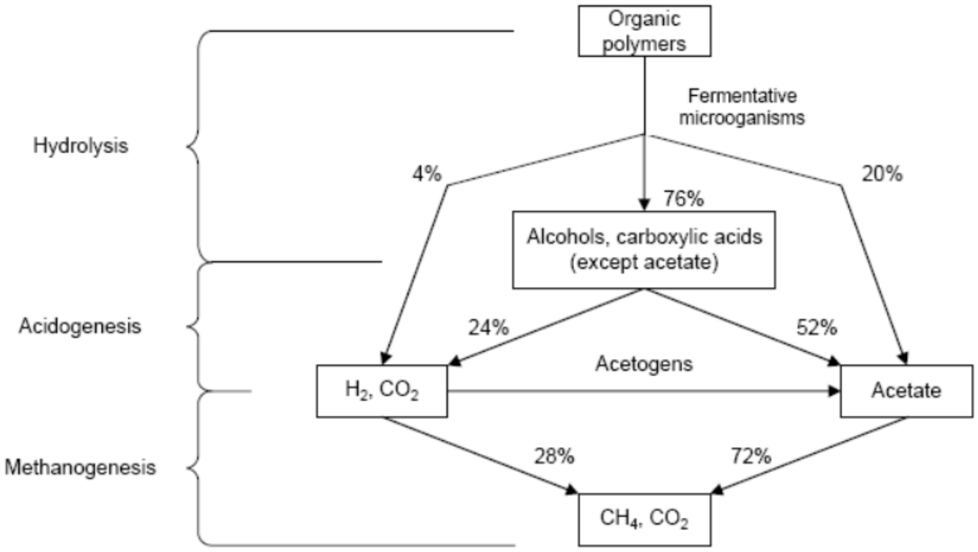


Figure 1: The Anaerobic Decomposition of Organic Matter (Zehnder, Ingvorsen, & Marti, 1982)

2 METHODOLOGY

2.1 SECONDARY SLUDGE DIVERSION

During the cooling trial secondary sludge was diverted from CWTP’s thermophilic stage to the trial mesophilic digester (Digester 4). This low temperature secondary sludge (approx. 12 °C) was fed directly into Digester 4 in combination with the higher temperature thermophilic sludge to bring the bulk temperature to the mesophilic temperature range (33 – 35°C). Throughout the trial the volume of secondary sludge diverted was calculated by energy balance. The diversion of sludge was carried out manually by CWTP operators each time feeding to Digester 4 occurred, which was approximately three times a day.

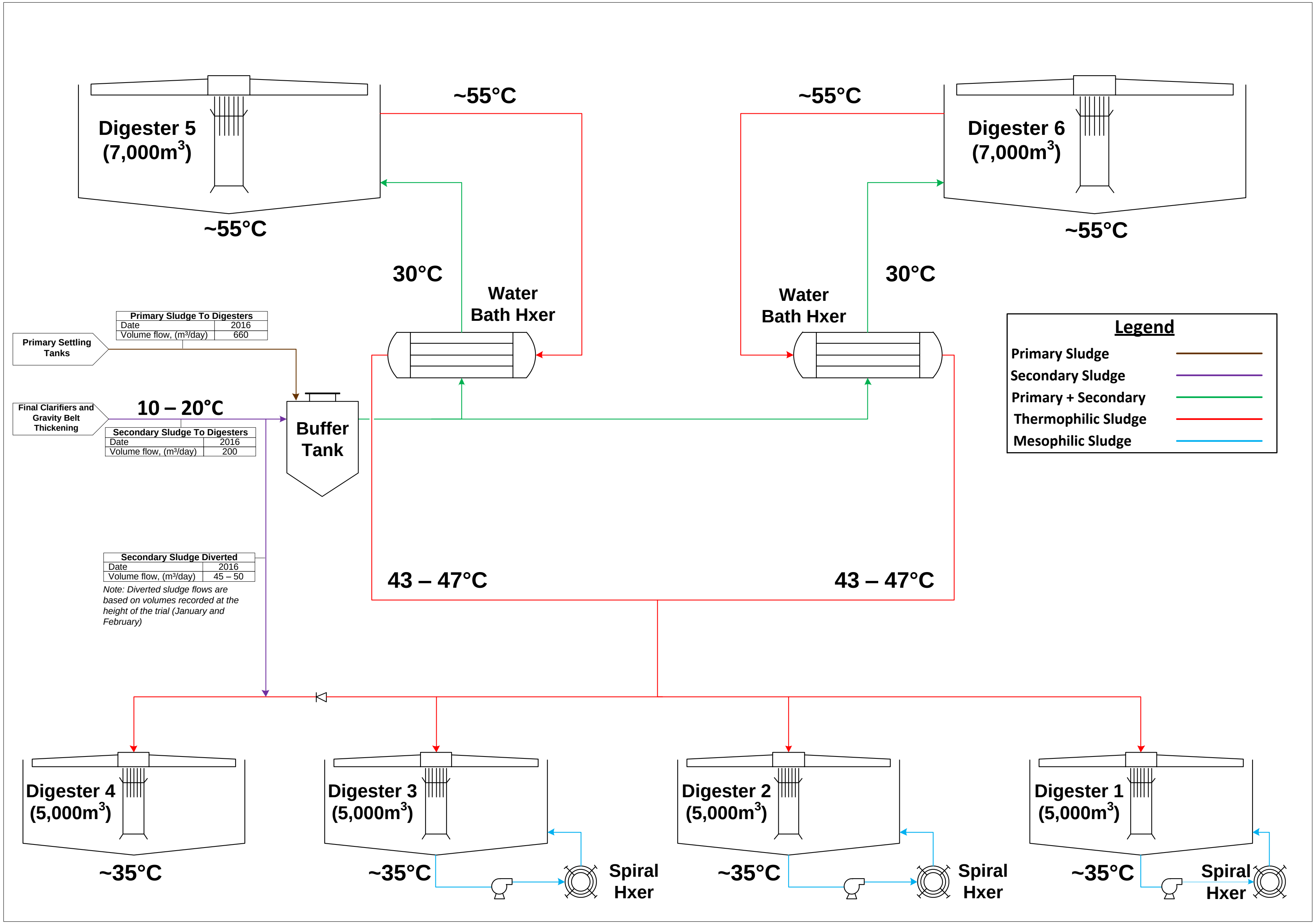
To mitigate the risk of shock loading for Digester 4, a ramp-up period was instated for six weeks at the beginning of the trial. During this ramp-up period the Digester 4 cooling heat exchanger was left in operation and the calculated volume of secondary sludge diverted was scaled by 20 – 100 %, ramping up as the trial progressed. After the ramp-up period, the digester's cooling heat exchanger was disabled and the cold secondary sludge provided all of the cooling for nine weeks. At the conclusion of this time Digester 4 was returned to normal operation.

2.2 TRIAL MONITORING

The CWTP laboratory undertook extensive sampling prior to, during and after the sludge cooling trial. This sampling was carried out to monitor digester health, operation and performance over the trial period. The streams sampled included sludge, dewatered biosolids and biogas streams. The following testing was carried out:

- pH;
- Dry solids (DS);
- Volatile solids (VS);
- Total volatile acids;
- Methane (CH_4);
- Carbon dioxide (CO_2);
- Hydrogen sulfide (H_2S).

In addition to laboratory data, significant use of sludge flow and temperature data measured by on-site instrumentation was collected.



Primary Sludge To Digesters	
Date	2016
Volume flow, (m³/day)	660

Secondary Sludge To Digesters	
Date	2016
Volume flow, (m³/day)	200

Secondary Sludge Diverted	
Date	2016
Volume flow, (m³/day)	45 – 50

Note: Diverted sludge flows are based on volumes recorded at the height of the trial (January and February)

Figure 2: Indicative Sludge Diversion PFD with Sludge Feed Flows

3 TRIAL OUTCOMES

3.1 INTRODUCTION

The operation of a high-rate anaerobic digestion system can be characterised by several factors (Metcalf & Eddy, 2003), these include:

- Organic loading rate;
- Volatile solids destruction;
- Biogas production;
- Biogas composition;
- Digested biosolids dewaterability;
- Digester pH;
- Digester volatile acid content.

The influence of modifying the operation of the mesophilic digesters on each of these properties was investigated in this trial and the outcomes are discussed below.

3.2 ORGANIC LOADING RATE

The organic loading rate (OLR) of a digester pertains to the amount of volatile solids in the digester's feedstock relative to the total digester capacity. Digesters are typically designed for an optimal OLR (Metcalf & Eddy, 2003). Too high loading can lead to the accumulation of toxic materials in a digester or the washout of methane formers where as too low loading rate can result in excessively large digesters (WEF, 1998).

Figure 3 shows the influence on the OLR of diverting secondary sludge to the mesophilic digesters. The recommended OLR limits (1.6 to 4.8 kg VS/m^3.d) provided in the Figure were retrieved from (Metcalf & Eddy, 2003) and apply to mesophilic digesters. It is not known what the recommended OLR for thermophilic operation is. From Figure 3 it can be seen that, at present, the thermophilic digesters operate within the band of recommended OLRs for mesophilic digesters. Conversely, the mesophilic digesters sit well below the recommended lower limit for OLR, even when being fed diverted secondary sludge. From this assessment it can be inferred that during the sludge trial, Digester 4 was not fed excessive volatile solids.

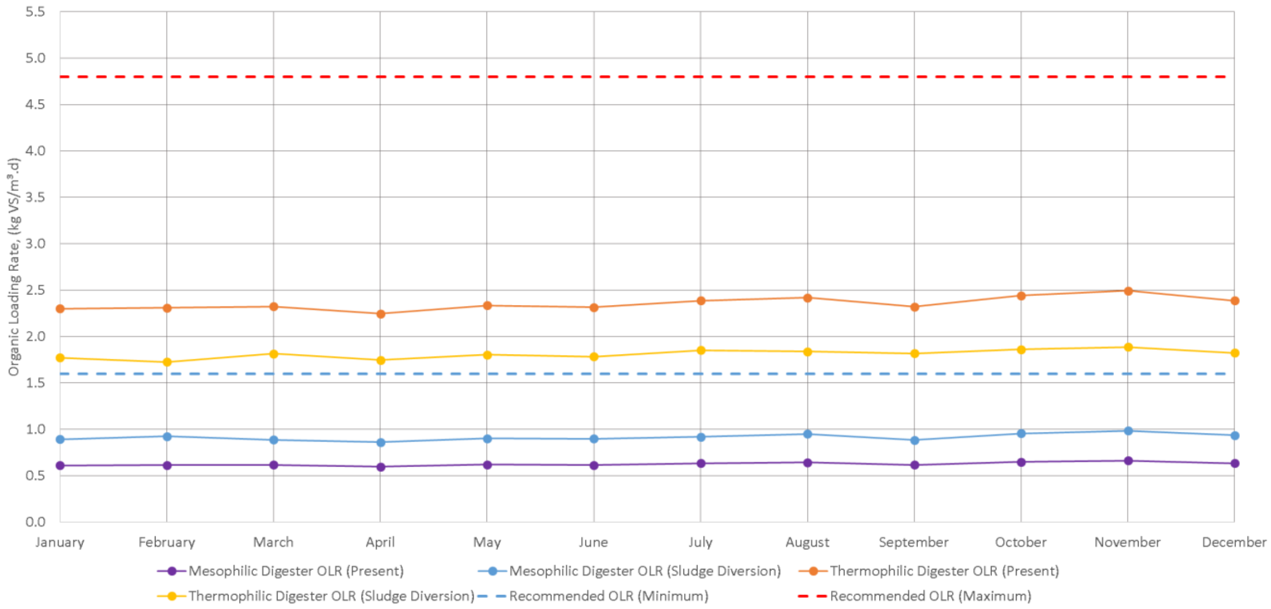


Figure 3: Monthly Digester OLRs Based on 2016 to 2017 Data

3.3 VOLATILE SOLIDS DESTRUCTION

Volatile solids represent the component of sludge solids that have the potential to undergo anaerobic digestion. In general, the overall extent of waste stabilization achieved by digestion is measured as a function of volatile solids destruction. Volatile solids destruction can also be used to assess biogas production from a digester, with literature providing correlations ranging from 0.75 – 1.12 m^3/kg of volatile solids destroyed (Metcalf & Eddy, 2003) (WEF, 1998) for digesters that process a mixture of primary and secondary sludge.

To estimate the volatile solids destruction in the digesters during the trial, dry solids and volatile solids data was used, see Figure 4 a and b. These figures show that after the trial commenced, the volatile solids destruction exhibited by Digester 4 increased significantly from approximately 17% prior to the trial, to between 30 – 45% around late January to mid-February. In comparison, the volatile solids destruction in Digester 1 (normal heat exchanger cooling) oscillated between 12 – 23% before increasing in late January to mid-February to 23 – 37%.

This suggests that after the introduction of secondary sludge to Digester 4, the microbial population quickly adapted to the altered feedstock. Furthermore, although the volatile solids destruction of both digesters increased in February, the increase in volatile solids destruction of Digester 4 over Digester 1 was generally maintained throughout the trial. Finally, after the trial end period, the volatile solids destruction of Digester 4 returned to its original range (similar to Digester 1).

The range of volatile solids destruction carried out by Digesters 5 and 6 remained relatively constant throughout the trial period. This indicates that altering the feedstock to the thermophilic digesters (by removing a portion of the secondary sludge) had negligible impact on their volatile solids destruction.

Figure 4 a and b: Volatile Solids Destruction for Digester 1 and 2 (a) and Digesters 5 and 6 (b)

3.4 BIOGAS

3.4.1 BIOGAS PRODUCTION

A significant benefit of anaerobic digestion is the formation of biogas that is rich in combustible methane. To investigate the influence of the sludge cooling trial on the production rate of biogas, CWTP biogas flowmeter data from November 2014 to June 2017 has been collected as summarised in Figure 5 a to d.

It is important to note that comparisons can only be drawn between biogas production for each digester from year to year, not between digesters. This is due to the variable accuracy of the flow meters used. For example, Figure 5 shows that for Digesters 1 and 4 (both mesophilic digesters which are typically operated in a similar manner with the same feedstock) Digester 1 yields biogas productions rates around 180,000 – 225,000 m³ per month while Digester 4 only produces 20,000 – 60,000 m^3 of biogas per month. Casual observations suggest that the biogas flows measured for Digester 4 are more accurate than those reported for Digester 1. Because of this inaccuracy, the data can only be used for year to year comparison of individual digesters.

From Figure 5 it can be seen that in general, biogas production from the thermophilic digesters decreased during the trial period compared to previous years. Digester 5 produced 340,000 m³ in January 2017, compared to 393,000 m³ in 2016 and 396,000 m³ in 2015. For the mesophilic digesters, Figure 5 does not show any discernible trend.

From the results discussed above it appears that the diversion of secondary sludge from Digesters 5 and 6 to Digester 4 led to a reduction in overall biogas production from the thermophilic digesters. It is unlikely that this was caused entirely by the sludge cooling trial as the average production in biogas from Digester 5 and 6 in the months leading up to the trial was lower than previous years, indicating that less biogas was being produced prior to the trial commencing. The reason for this has not been established.

3.4.2 BIOGAS COMPOSITION – METHANE AND CARBON DIOXIDE

An additional measure of digester performance is gas composition, as this provides insight into the activity of different microbial populations, notably the acetogens and methanogens. Furthermore, healthy mesophilic digesters generally producing biogas with methane (CH_4) and carbon dioxide (CO_2) concentrations in the order of 60 – 70% and 30 – 35% by volume respectively (WEF, 1998).

Figure 6 shows that over the trial period, the composition of each biogas stream measured remained relatively constant. The mesophilic and thermophilic digesters exhibited methane compositions in the order of 66 – 67% and 61 – 62% respectively, with the balance comprised of carbon dioxide. Thus, it can be concluded that diverting secondary sludge to Digester 4 had no noticeable effect on the biogas composition.

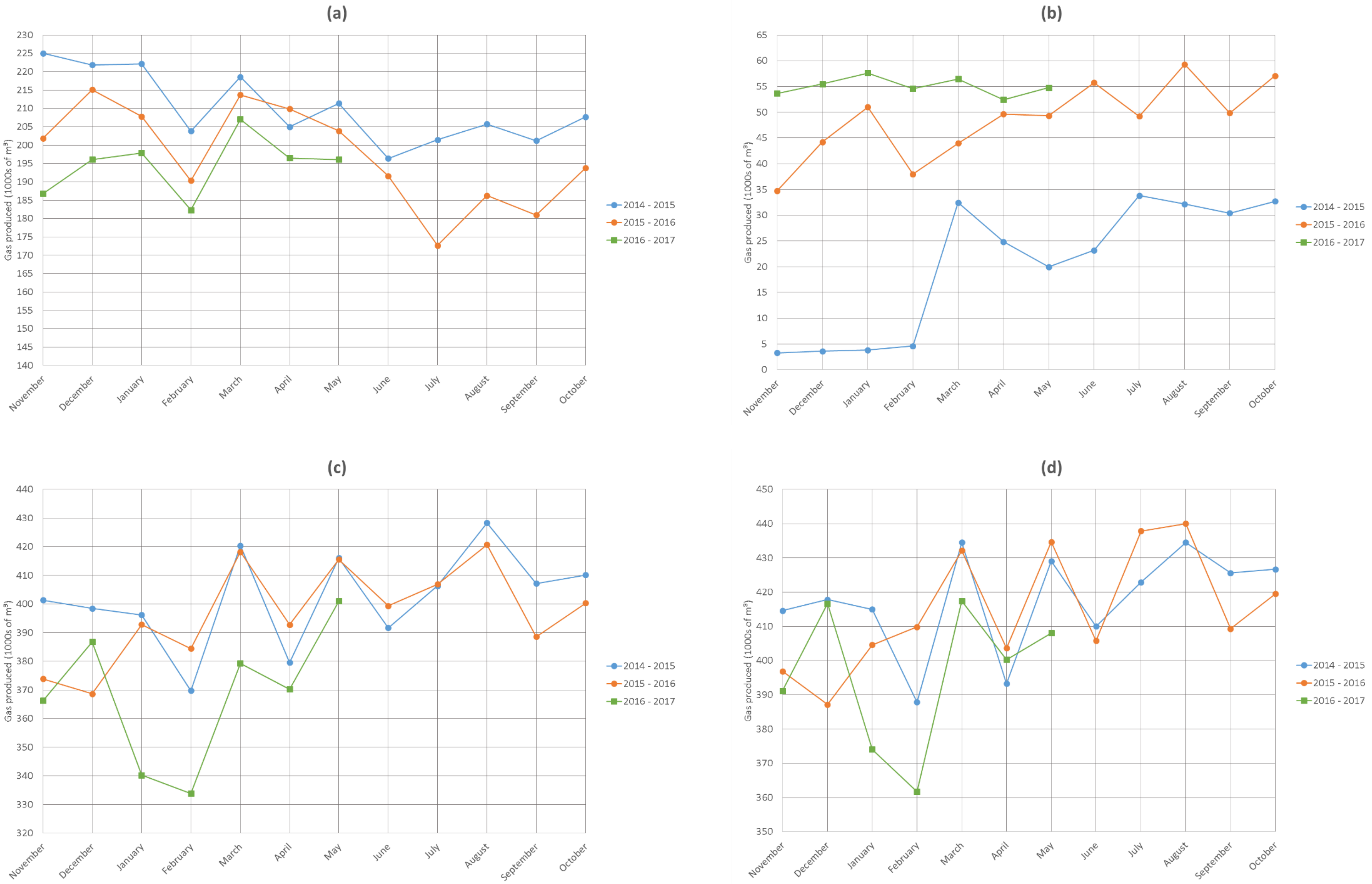


Figure 5: Monthly Biogas Production Rates for Digester 1 (a), Digester 4 (b), Digester 5 (c) and Digester 6 (d)

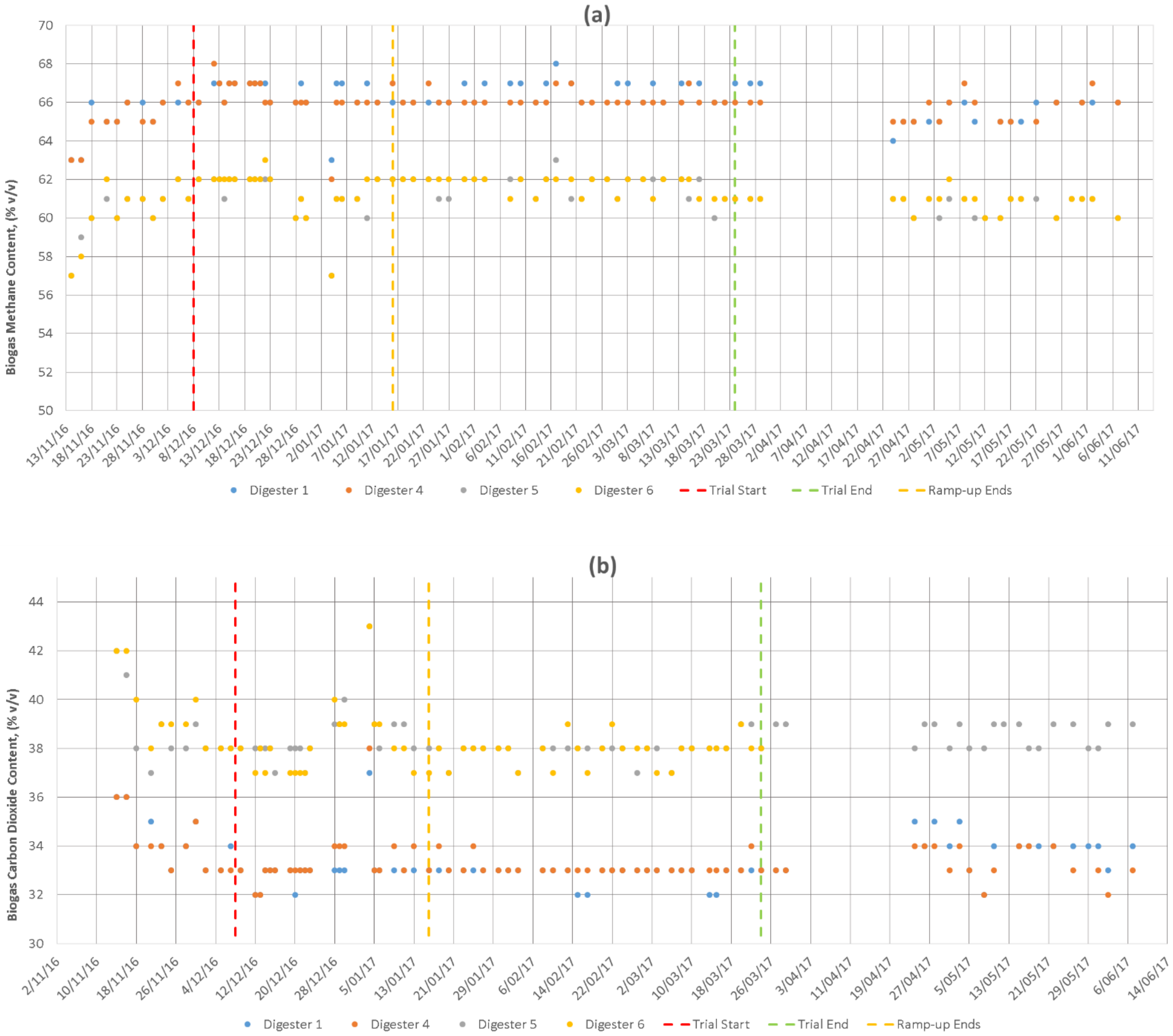


Figure 6: Digester Biogas CH_4 (a) and CO_2 (b) Content over the Trial Period

3.4.3 BIOGAS COMPOSITION – HYDROGEN SULFIDE

Municipal wastewater contains oxidised sulfur compounds such as sulfate (SO_4), sulfite (SO_3^{2-}) and thiosulfate ($S_2O_3^{2-}$). These compounds undergo reactions with sulfur reducing bacteria in the presence of acetic acid to produce hydrogen sulfide. Depending on the pH, this hydrogen sulfide is present in solution as either a gas (H_2S), an ion (HS^-), or as sulfide ions (S^{2-}). Gaseous hydrogen sulfide can then enter the gas phase depending on the dissolved to free gas phase-equilibrium (see Figure 7).

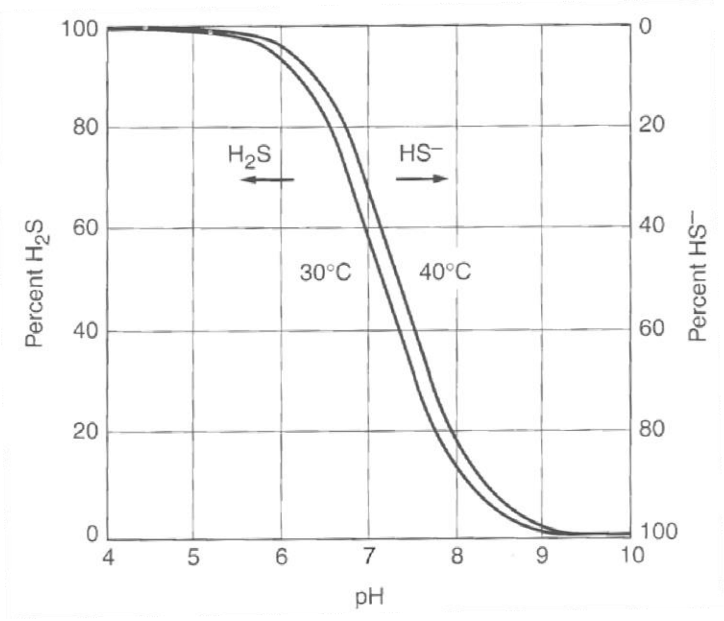


Figure 7: Hydrogen Sulfide Phase Equilibrium as a Function of Sludge pH (Metcalf & Eddy, 2003)

Biogas produced through anaerobic digestion typically contains notable concentrations of hydrogen sulfide. Although still corrosive at ambient temperatures and pressures, this compound has the potential to cause significant corrosion at high temperatures. This is of particular risk to engine components which come into contact with hydrogen sulfide raised to combustion temperatures Additionally, the combustion of hydrogen sulfide leads to the formation of sulfhur oxides (SOx), a class of gasses that contribute to acid rain formation and are considered to be air pollutants (US EPA, 2016).

Figure 8 provides hydrogen sulfide data over the trial period. It can be seen that the concentration of hydrogen sulfide in the biogas produced by Digester 4 decreased dramatically from 360 – 500 ppm prior to the trial period to 0 – 140 ppm for the first two months of the trial. There are several possible factors that could have caused this hydrogen sulfide reduction. The ratio of decomposable organic and inorganic material to sulfate ratio in the feed to an anaerobic digester can have a significant effect on the amount of sulfur reduction achieved, as sulfate-reducing bacteria compete with methanogens (McDonald, 2007). The chemical oxygen demand (COD) increased in the feed to Digester 4 over the trial period, and this may have brought about an optimal COD/sulfate ratio where methanogenesis dominated the competition for COD. Alternatively, it may be that the secondary sludge at CWTP maintains a lower concentration of oxidised sulfur compounds than primary sludge. This would simply mean that less sulfur would be available in Digester 4 for reduction into hydrogen sulfide. More investigation is required to confirm the cause.

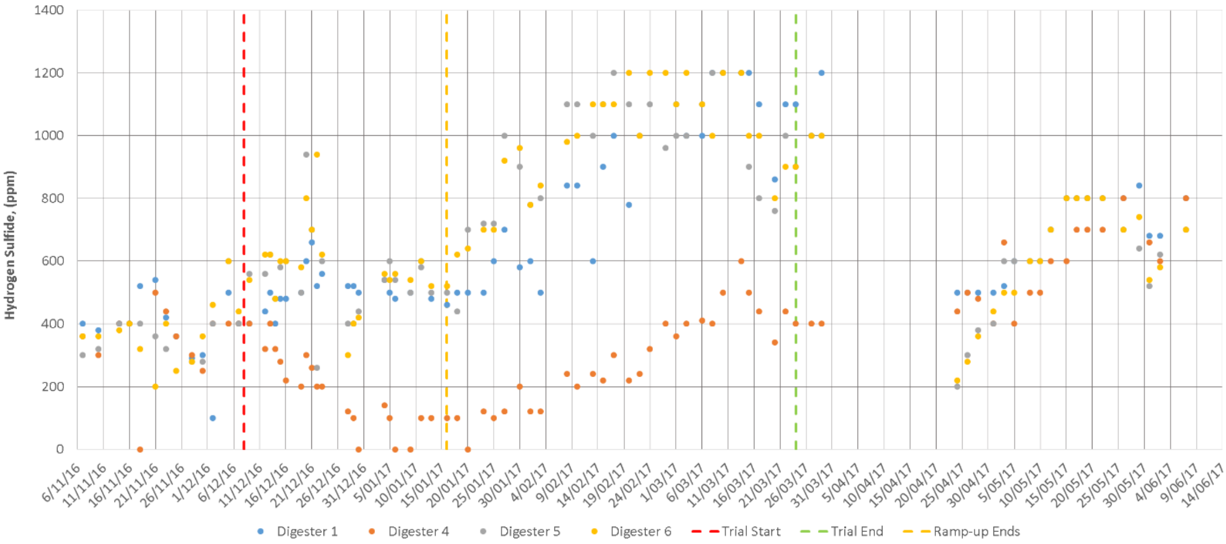


Figure 8: Digester Biogas Hydrogen Sulfide Data over the Trial Period

Later in the trial, the hydrogen sulfide content of all measured biogas streams on-site increased dramatically, with biogas from Digesters 1, 4 and 5 all reaching a maximum of 1200 ppm and Digester 4 biogas reaching a maximum of 600 ppm. It should be noted that during this period, the average hydrogen sulfide content of Digester 4 biogas still remained significantly lower than the other digesters until after the trial period, where all of the digesters exhibited similar values.

It is likely that the subsequent rise in the hydrogen sulfide content of each digester's biogas was caused by external factors, such as changes in the influent to CWTP from upstream tradewaste discharges. This is demonstrated by Figure 9, which shows that the digesters exhibited three similar peaks in hydrogen sulfide content during 2016.

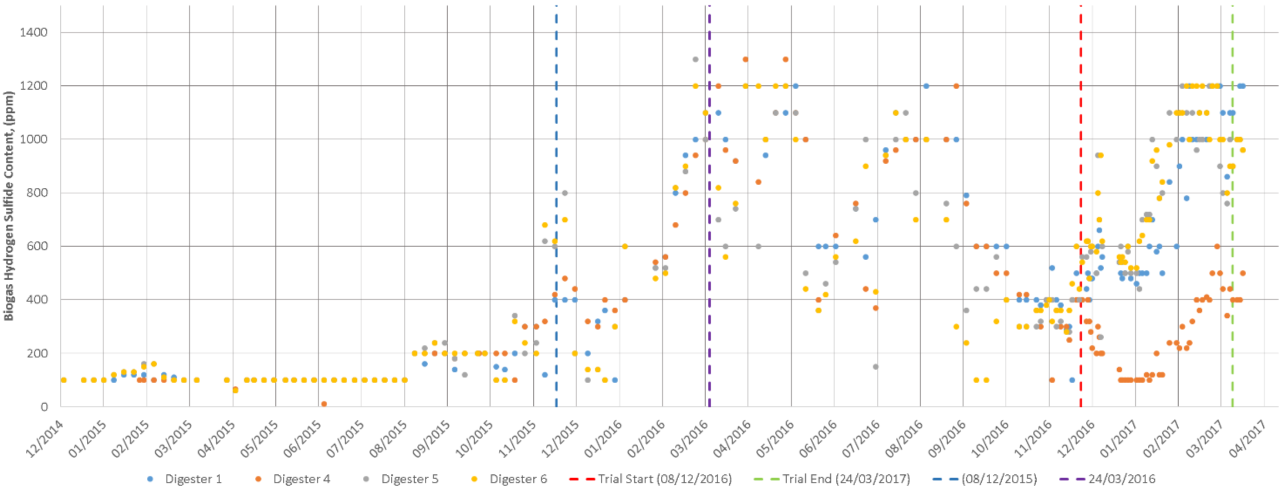


Figure 9: CWTP Digester Biogas Hydrogen Sulfide Data from 2015 – 2017

3.5 SLUDGE DEWATERING

CWTP operates two belt presses in parallel to dewater digested biosolids drawn from the mesophilic digesters prior to drying. The operation of these belt presses is manually fine-tuned by the operators during the day.

A potential risk identified for the sludge cooling trial was a reduction in the dewaterability of digested biosolids from Digester 4. Secondary sludge contains more cell material than primary sludge. During normal operation of the CWTP digestion process, this cellular material passes through both the thermophilic and mesophilic digesters in series, providing maximum opportunity to be broken down. During the trial, Digester 4 contained sludge that only received mesophilic digestion, increasing the likelihood of poor destruction of the cell material.

Figure 10 provides a summary of dewatering during the trial period. It is important to note that it is not known which digester was feeding the belt presses when the dewatered biosolids sample were retrieved (this data is not collected by the SCADA). From this data it can be seen that prior to commencing the trial, the dry solids content of the dewatered biosolids remained fairly consistent around 20 – 22%. During the trial the dry solids content became more variable, ranging from 18 – 26%. This variability reduced again after the trial period. In order to derive a conclusion from this data, several factors should be considered:

- It is not known whether the samples with the reduced DS content were retrieved when Digester 4 was feeding the dewatering process.

- It is not known if the low DS content of these samples came about as the result of an increase in cellular material in the digested biosolids or non-ideal belt press operation at the time the samples were taken. During the trial one of the site’s two belt presses was off line for significant maintenance.

- Anecdotal evidence from CWTP operators suggests that the dewaterability of biosolids from Digester 4 decreased.

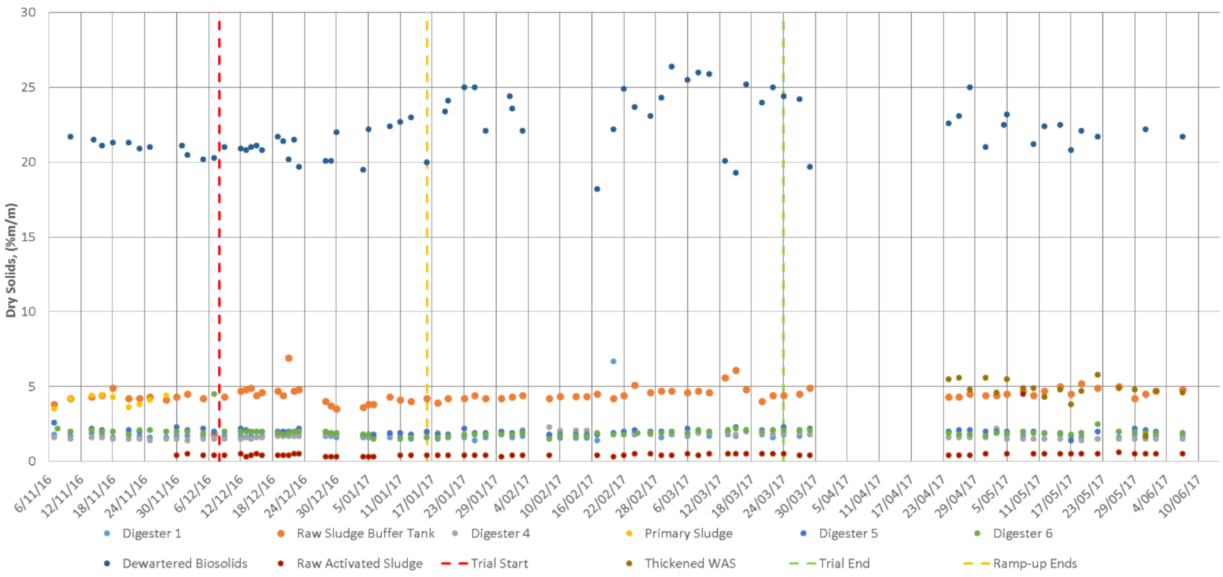


Figure 10: Secondary Sludge Diversion Trial Dewatering Data

Figure 10 indicates that there was increased variability of the dry solids of the dewatered sludge. This suggests that the dewaterability of biosolids from Digester 4 was different. This is difficult for operators to manage as the operating point for the belt presses changed every time Digester 4 sludge was being dewatered. If all four mesophilic digesters used sludge cooling the composition would be constant and the belt presses optimised for this.

3.6 SLUDGE pH

Carbon dioxide produced during acidogenesis and methanogenesis has the potential to dissolve into digester sludge and convert to carbonic acid. Hence the carbon dioxide content of digester gas is indicative of alkalinity requirements within the digester of origin. Ultimately, any shift in carbonic acid production will eventuate in a change in the pH of the digester sludge and indicate whether a digester upset has occurred.

Further evidence of a digester upset can be derived from changes in pH, as this could be brought about through an interruption to part of the metabolic chain. For example, a decrease in pH may indicate an accumulation of carboxylic acids and a lack of acidogenesis occurring.

Figure 11 provides pH information for the four digesters tested. From this Figure, it can be seen that the pH of Digester 4 remained relatively stable throughout the trial and exhibited similar noise to before the trial's commencement, indicating that the diversion of secondary sludge to this digester did not alter pH.

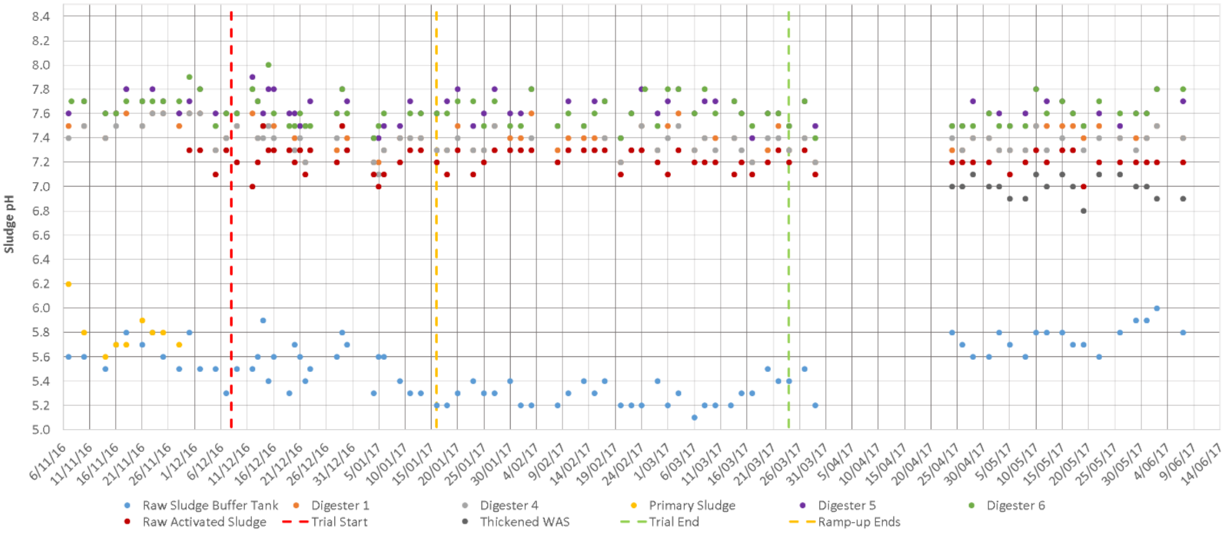


Figure 11: Sludge Stream pH Data Over the Trial Period

3.7 VOLATILE ACIDS CONCENTRATION

Similarly to pH, a change in the volatile acids concentration in a digester can provide insight to the activity of the microbial population. An increase in volatile acids concentration indicates either a decrease in acidogenesis or an increase in acid formation (hydrolysis). A decrease in volatile acids concentration would then imply the opposite were occurring.

Figure 12 indicates that for each digester, the volatile acids concentration remained low, and did not vary greatly from pre-trial measurements despite significant fluctuations in the volatile acid concentration of the buffer tank sludge fed to the thermophilic digesters.

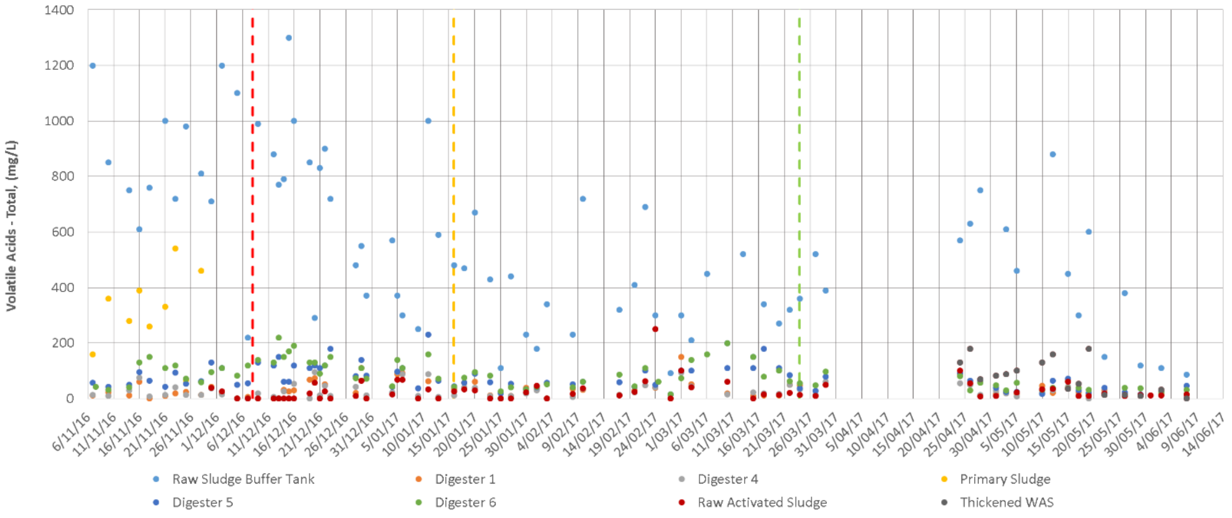


Figure 12: Sludge Stream Volatile Acids Concentration

4 CONCLUSIONS

A full scale trial was conducted at the CWTP to investigate the feasibility of cooling the thermophilic sludge feed to the mesophilic digesters using cold secondary sludge. During this trial stable operation of the trial mesophilic digester (Digester 4) was maintained. The data gathered during the sludge cooling trial suggests that the microbial populations contained within the digester responded favourably to the altered feedstock.

The volatile solids destruction in Digester 4 increased from 17% before the trial to around 30 – 45% during the sludge cooling trial, indicating a positive response from the microorganisms to the new feedstock. Volatile solids destruction rates achieved by the thermophilic digesters did not appear to change as a consequence of the sludge diversion.

Over the trial period the OLR of Digester 4 was well below the minimum recommended by literature of 1.6 kg VS/m³, giving further credence to the conclusion that Digester 4 was able to metabolise the altered feedstock because it was not being over fed.

The overall biogas production at CWTP over the trial period was lower than production rates measured over 2014 to 2016 (in the order of 50,000m³ per month). However, it was concluded that this was not likely caused by the sludge cooling trial as biogas production rates were already lower before the trial commenced. A cause for the reduction was not identified.

The altered feedstock to Digester 4 did not result in any significant variation in the methane and carbon dioxide composition of the biogas produced by any of the digesters. Conversely, a significant reduction the hydrogen sulfide content of biogas from Digester 4 was observed. Reducing from 360 – 500 ppm before the sludge diversion, to 0 – 140 ppm during the trial. It was proposed that the initial reduction in hydrogen sulfide content could have been caused by two phenomena; 1) competition between sulfur reducing bacteria and methanogens population, and 2) the diverted secondary sludge may contain less sulfur oxidised compounds than the sludge drawn from the thermophilic digesters. Further investigation is required to establish the cause of the reduced hydrogen sulfide.

No negative impact on digester pH or volatile acids was observed during trial period, indicating that no significant metabolic change in microbial activity occurred.

Finally, it appeared that the dewaterability of the digested biosolids drawn from Digester 4 may have reduced as a consequence of the sludge diversion. Sludge dewatering would need to be optimised if all four digesters are converted to secondary sludge cooling. The recommended outcome of the trial was that all four mesophilic digesters be operated using secondary sludge cooling.

5 REFERENCES

City Solutions and CH2M Beca. (2006). *Christchurch Wastewater Treatment Plant - Digester 5/6 Design Report.* Christchurch: City Solutions and CH2M Beca.

Gujer, W., & Zehnder, A. J. (1983). *Conversion Processes in Anaerobic Digestion.* IWA.

Lu, J., & Ahring, B. K. (2007). *Optimization of Anaerobic Digestion of Sewage Sludge Using Thermophilic Anaerobic Pre-Treatment.* Copenhagen: Technical University of Denmark.

McDonald, H. B. (2007). *The effect of sulfide inhibition and organic shock loading on anaerobic biofilm reactors treating a low-temperature, high-sulfate wastewater.* Iowa City: University of Iowa.

Metcalf & Eddy. (2003). *Wastewater Engineering - Treatment and Reuse (4th ed).* New York: McGraw-Hill.

US EPA. (2016, August 16). *Sulfur Dioxide (SO2) Pollution*. Retrieved from United States Environmental Protection Agency: https://www.epa.gov/so2-pollution/sulfur-dioxide-basics#effects

WEF. (1998). *Design of Municipal Wastewater Treatment Plants - Volume 3 (4th ed).* Washington: Water Environment Federation.

Zehnder, A. B., Ingvorsen, K., & Marti, T. (1982). *Microbiology of methanogen bacteria, in anaerobic digestions.* Amsterdam: Elsevier.