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FOAMING IN AN INNOVATIVE ANAEROBIC MEMBRANE BIOREACTOR TREATING HIGH SOLIDS WASTEWATER

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Abstract: An innovative anaerobic membrane bioreactor (AnMBR) using an external tubular nanofiltration membrane module is being operated under mesophilic conditions for the treatment of a high-solids wastewater (influent total suspended solids (TSS) of 5658 mg/L (± 1771 mg/L) and a chemical oxygen demand (COD) of 84,156 mg/L (± 4570 mg/L)) to determine operational conditions required to achieve good system stability while minimizing the reactor foaming propensity. The system configuration consists of a 1000 L continuous stir tank reactor (CSTR) equipped with an external tubular membrane. Thus far, operation at organic loading rates (OLR) in the range of 0.8 – 8.2 $kg/m^3 \bullet d$, and a concentration of mixed-liquor suspended solids (MLSS) in the range of 13.6 – 33.9 g/L, have been studied. Throughout the duration of the study five events of excessive foaming were recorded. Excessive foaming events were defined as events where both the primary and back-up gas traps were filled with foam, and additional foam poured down the sides of the reactor through gaps between the CSTR cover and wall created during these instances of excessive foaming. Increases (shock) in OLR, temperature, reactor ammonia nitrogen and total alkalinity concentrations, and the accumulation of colloidal materials within the reactor have all been known to impact reactor foaming propensity. This research project found shock increases in OLR, and its associated accumulation of colloidal materials, to be the most influential factor affecting reactor foaming propensity. Following an analysis of the causation of each excessive foaming event, a mitigation plan was developed to prevent future foaming events.

Keywords: Anaerobic membrane bioreactor, High-solids wastewaters, Foaming, Shock loading, Temperature.

1 INTRODUCTION

Anaerobic bioreactor technologies for the treatment of wastewaters offer advantages over traditional aerobic wastewater treatment systems such as high rate suspended growth systems, high removal efficiencies of biochemical oxygen demand (BOD) and chemical oxygen demand (COD), resource recovery (methane in biogas and value added chemicals), low sludge yield, and low carbon footprint, (Kinnunen et al. 2015, Ozgun et al. 2013, Pilli et al. 2016, Meng et al. 2009, and Skouteris et al. 2012). Additionally, the integration of membrane technologies within anaerobic bioreactors offer advantages over non-membrane integrated anaerobic bioreactor wastewater treatment systems such as high biomass retention (independent of sludge settle-ability through the membrane's complete solid-liquid separation capabilities), compact design, and most importantly the ability to produce a superior quality effluent for possible recycle or high quality discharge.

An operational issue that has been common to anaerobic membrane bioreactors (AnMBRs) since their first applications is bioreactor foaming. Foaming in AnMBRs results from a complex three-phase phenomenon (liquid-solid-gas) contributed from surface-active materials and water in sludge, as well as biogas generated through the anaerobic digestion pathway (Subramanian and Pagilla 2015). Reactor foaming causes inefficient gas recovery from the digester, reduction in the active digester volume, mechanical blockages, fouling of gas pipes, and the loss of biomass from spill carry-over (Ganidi et al. 2009, Kale and Singh 2016, Subramanian and Pagilla 2015, and van Niekerk et al. 1987).

Although foaming has been studied extensively, and factors having a tendency to affect its propensity have been identified, further studies into which of these factors contribute the most significantly towards this operational issue would help develop control mechanisms to prevent it. The goal of this study is to evaluate instances of excessive bioreactor foaming exhibited during the operation of a pilot-scale AnMBR system integrated with an external nanofiltration tubular membrane for the treatment of a high-solids wastewater. Instances of excessive bioreactor foaming will be evaluated to gain a better understanding into what causes this operational issue, and to develop a mitigation strategy to prevent this issue in future operations and applications.

2 MATERIALS & METHODS

2.1 Pilot-scale study

The pilot reactor configuration used for the duration of the experiment consists of a 1000 L stainless steel complete stir tank anaerobic reactor (CSTR), equipped with an external tubular nanofiltration membrane unit capable of backwashing processes. The reactor contents are maintained at 36°C, providing mesophilic conditions. The schematic flow diagram of the experimental set-up is shown in Figure 1.

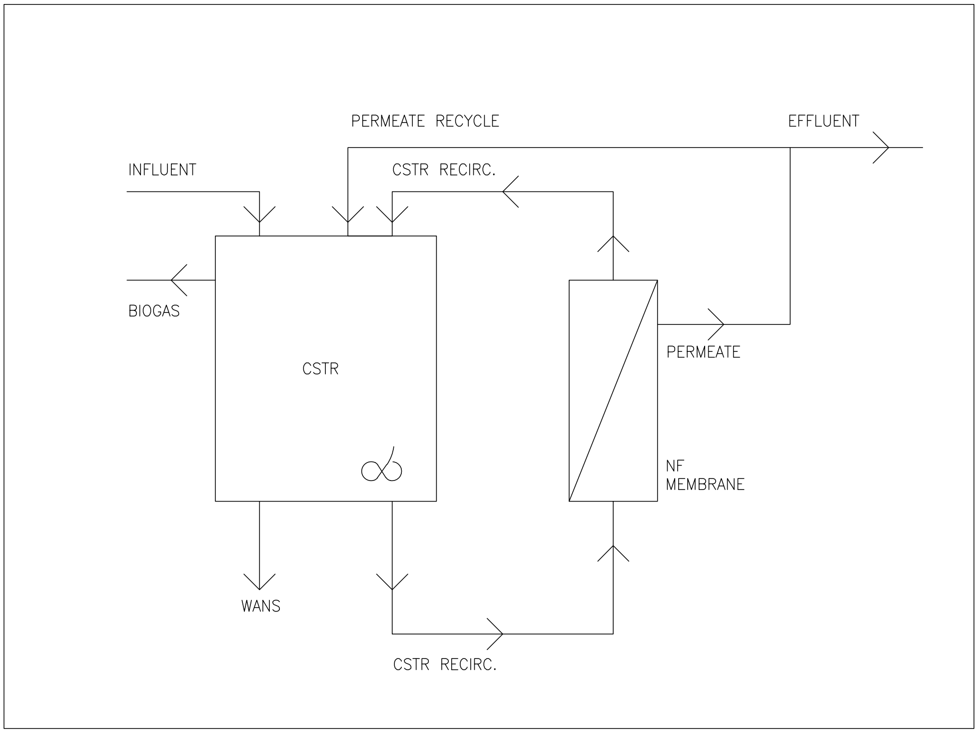

Figure 1: Schematic flow diagram of experimental set-up.

The CSTR contents are circulated through the external tubular membrane unit where a portion flows through the membrane unit, being removed as permeate, and the rest is recycled back into the CSTR.

Permeate is then wasted as effluent or backwashed through the membrane to remove reversible membrane fouling.

2.2 Seed sludge & Synthetic wastewater

The CSTR was seeded with a granular sludge obtained from an anaerobic digester treating wastewater generated during fruit-juice production. The seed sludge was run through a coarse metal screen prior to seeding to remove larger granules, and other suspended matter. The seed sludge was then circulated in the CSTR prior to membrane attachment, to allow it to develop into its own culture without granules. Reactor mixed liquor suspended solids (MLSS) has varied from a minimum value of 13.6 g/L to a maximum value of 33.9 g/L, with an average of 23.8 g/L (± 5.0 g/L).

The CSTR is fed a synthetic wastewater composed of both particulate (supplied through potato starch) and soluble (supplied through granulated sugar) chemical oxygen demand (COD). Macronutrients are supplied continuously in the influent synthetic wastewater, and micronutrients are bulk-dosed based on the COD loading fed to the system on a weekly basis. A partial characterization of the synthetic influent wastewater may be viewed in Table 1.

Table 1: Partial characterization of the synthetic wastewater.

Parameter	Unit	Value	
		(Avg.)	(S.D.)
Chemical Oxygen Demand (COD)	mg/L	84,156	± 4570
Particulate COD	mg/L	4900	± 2073
Filtered COD	mg/L	79,256	± 4278
Soluble COD	mg/L	79,058	± 4108
Total Suspended Solids (TSS)	mg/L	5658	± 1771
Volatile Suspended Solids (VSS)	mg/L	5632	± 1868

2.3 Analysis

CSTR operational flows and pressures are collected daily and displayed through a PLC system. Influent, effluent, and CSTR contents have their water quality parameters analysed according to HACH Water Analysis Handbook and Standard Methods for the Examination of Water & Wastewater (Hach Company 2002, and Eaton et al. 2005). Biogas production rate is monitored using an AALBORG Mass Flow Meter (GFM) calibrated for a gas possessing a composition of 70% CH_4 and 30% CO_2. To gauge the actual methane content of the biogas being produced, gas samples are collected weekly and their composition is determined using a combination of gas reaction tubes and a Varian CP-3800 gas chromatography machine. When foaming was present, it was collected through buckets located beneath the CSTR if possible.

3 RESULTS & DISCUSSION

3.1 Reactor foaming

There are a number of factors that have been identified to contribute towards foaming in anaerobic reactor systems. Amongst these factors are rapid (shock) increases in organic loading rate (OLR), temperature changes, and the accumulation of alkalinity, ammonia nitrogen, and colloidal material (Ganidi et al. 2009, Kale and Singh 2016, Subramanian and Pagilla 2015, and van Niekerk et al. 1987). Although exact volumes of foam were not able to be collected, the foaming events that occurred throughout the operation of the pilot-scale AnMBR may be categorized into two primary categories. The first category is small foaming events, where only the primary gas trap was filled with foam. These foaming events resulted in minimal biogas losses, and were remediated quite quickly. The second category is excessive foaming events, where both the primary and back-up gas traps were filled with foam, and additional foam poured down the sides of the reactor through gaps between the CSTR cover and wall created during these instances of excessive foaming. In a full-scale system, these excessive foaming events would likely be sufficient to force either system shutdown, or result in large energy losses through the biogas collection issues associated with them and loss of reactor biomass. There were five events of excessive foaming noted, and they occurred on days 17, 28, 42, 100, and 116, with day 100 being an event large enough to force the pilot-scale system shutdown. Operational data from February 22nd – August 8th, 2016, will be examined with a specific focus on reactor temperature, OLR, alkalinity, ammonia nitrogen, and the potential for the accumulation of colloidal material leading up to each excessive foaming event. The goal will be to establish a primary causation for each excessive foaming event to develop mitigation strategies to prevent future events.

3.1.1 Organic loading rate (OLR)

A number of researchers have remarked that a shock loading in the feed supplied to an anaerobic digester may result in foaming due to an excess of compounds not being readily degraded by the bacteria, which then causes an abrupt accumulation of surface active by-products (surfactants) (Ganidi et al. 2009). As may be viewed in Figure 2 there were a number of instances where foaming was noticed after a shock loading was applied.

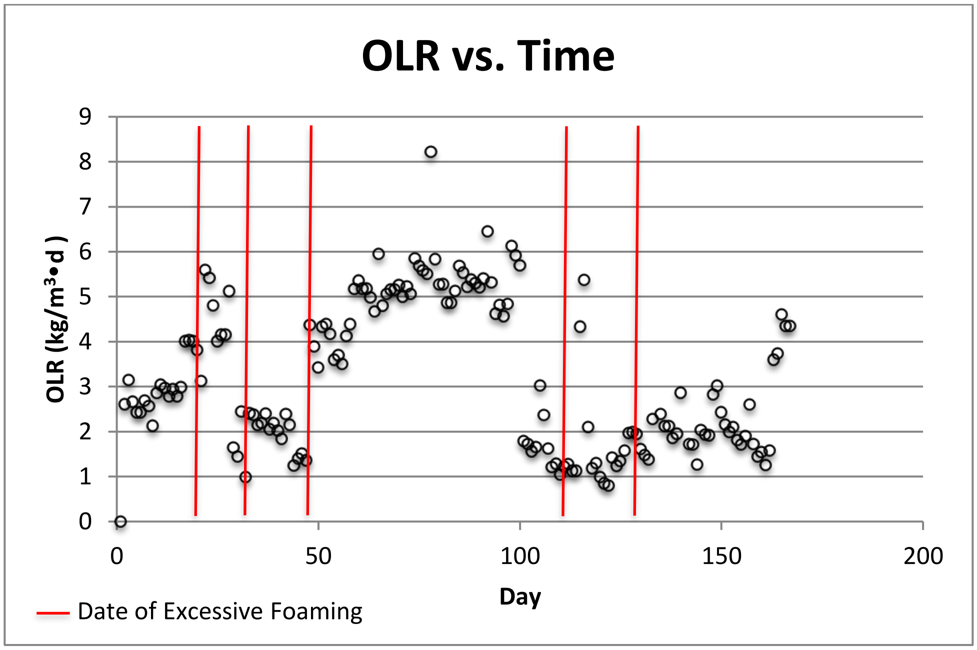

Figure 2: Organic loading rate (OLR) vs. time throughout the study period.

The excessive foaming on days 17, 28, 42, and 116 may be due entirely or partially to a shock in loading rate. On days 17, 28, 42, and 116, the OLR was raised by 135% (1.0 kg/m^3•d), 123% (1.0 kg/m^3•d), 131% (0.6 kg/m^3•d), and 124% (1.1 kg/m^3•d), respectively, which is quite a large increase in loading rate for a day-to-day basis. As the influent wastewater is composed of both a soluble sugar and particulate starch fraction, the shock load's soluble sugar portion would first be prioritized for bacterial anaerobic digestion. This would result in an abrupt accumulation of particulate starch COD, or in other words, surfactants, providing additional nucleation sites for gas bubbles in the sludge, and resulting in sudden foaming. The tendency of a reactor to foam has been noted to increase with an increasing suspended particulate concentration (Subramanian and Pagilla 2015). The only excessive foaming event where a spike in OLR was not exhibited prior to the foaming event was day 100, the day with the greatest amount of foaming. As it will be noted later, this day had many other factors contribute towards the quantity of foaming yielded.

3.1.2 Temperature

Reactor temperature has been found to have both a positive and negative effect on foaming propensity in an anaerobic digester. With a rapid increase in temperature, both the rate of gas bubble formation, and the rate of conversion of complex substrates to volatile fatty acids and biogas increase rapidly, increasing foaming tendency (Subramanian and Pagilla 2015). If a reactor were operated under thermophilic conditions, and compared to another reactor operating at mesophilic conditions, the thermophilic reactor would have a lower foaming tendency due to its lower viscosity providing better foam drainage and sludge breakup (Ganidi et al. 2009). A profile of the reactor temperature over the duration of the study may be viewed in Figure 3.

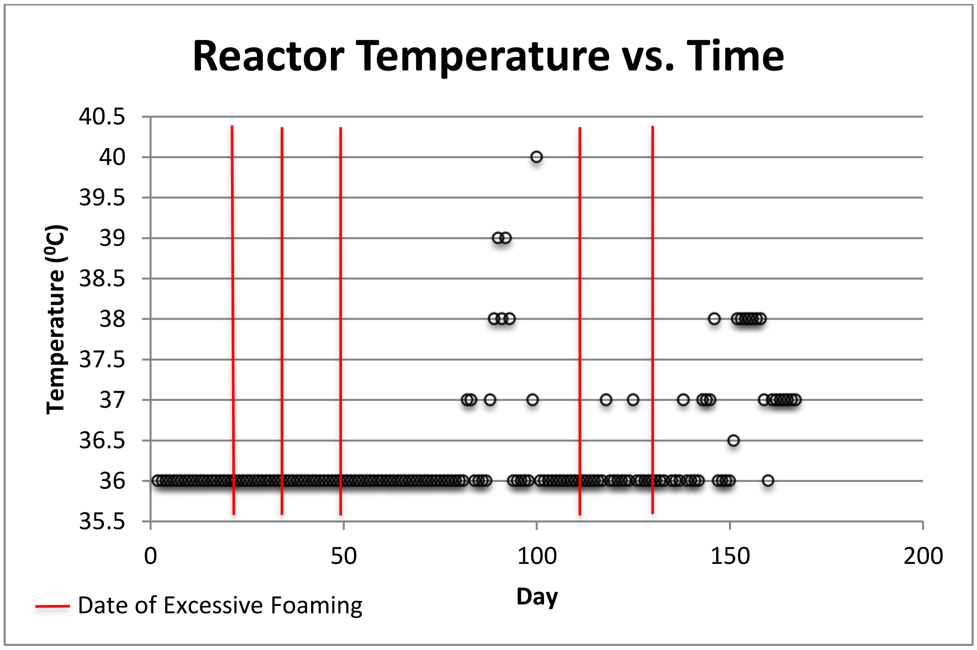

Figure 3: Reactor temperature vs. time throughout the study period.

As seen in Figure 3, there were a number of spikes in reactor temperature throughout the duration of the study, however excessive foaming was only exhibited when the reactor temperature jumped by 4°C over two days. It should be noted that when the reactor temperature increased to 39°C minor foaming events were present. However the temperature remained at 36°C for all other excessive foaming events. Due to other excessive foaming events taking place without a spike in temperature, and other minor temperature changes not causing excessive foaming events, it may be concluded that although an increased reactor temperature may contribute towards an increased foaming propensity, minor fluctuations in its value do not initiate reactor foaming. Large fluctuations may initiate a foaming event however, if other reactor characteristics are present to simultaneously contribute towards the foaming event.

3.1.3 Total Alkalinity

Reactor sludge alkalinity level has been proposed to be inversely proportional to reactor surface tension, therefore making sludge with a higher alkalinity concentration more surface active, and increasing its foaming propensity (van Niekerk et al. 1987). Reactor alkalinity was measured throughout the duration of the experiment, and may be viewed in Figure 4.

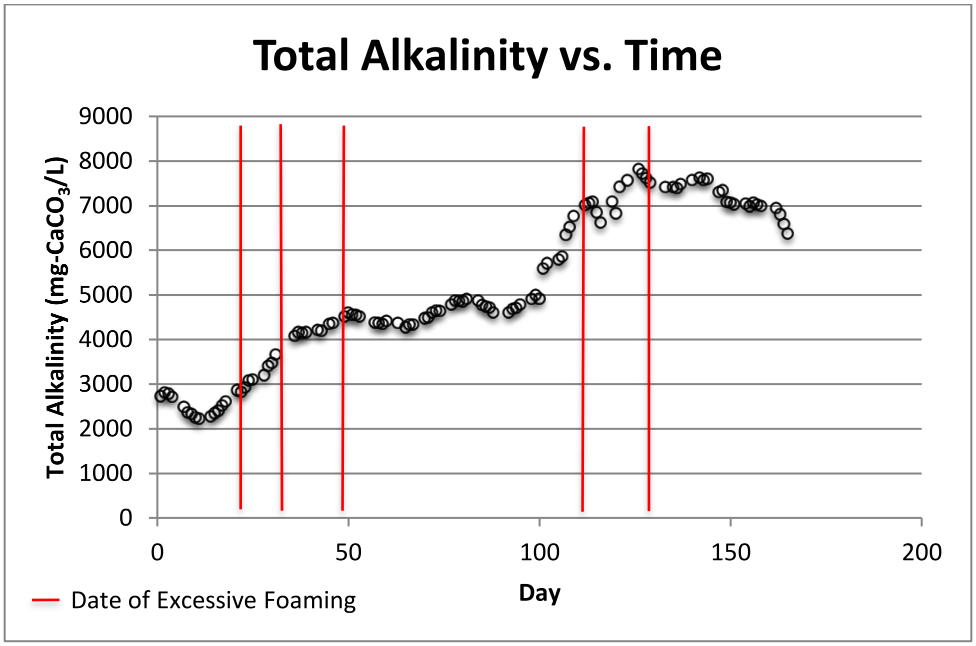

Figure 4: Reactor total alkalinity level vs. time throughout the study period.

Throughout the duration of the study, the total alkalinity level of the reactor was on a relatively steady increase, with there being a few periods where total alkalinity increased rapidly. Alkalinity accumulated in the beginning of the study because initial sludge wastage rate was very low (1 – 2 liters of sludge wasted per day). During days 30 – 100, sludge wastage rate was raised to an average of 21.1 L/d (± 10.1 L/d), which is why the alkalinity accumulation rate steadied out during this period. On day 100, the alkalinity level in the reactor was at its maximum of 4909 mg-$CaCO_3$/L when the largest excessive foaming event took place. Immediately following this event, sludge wastage rate was decreased by 62% (18 L/d), causing alkalinity to increase rapidly to 5583 mg-$CaCO_3$/L, and kept increasing for the next 23 days.

Although total alkalinity increases have been known to increase reactor foaming propensity, they do not appear to trigger excessive foaming events during the duration of this study. The largest foaming events did take place when alkalinity was at its highest levels in the reactors, but abrupt increases did not result in excessive foaming events. It would appear that larger foaming events take place when the reactor total alkalinity concentration is at its highest level, however further data should be collected to support this observation.

3.1.4 Ammonia Nitrogen

High ammonia nitrogen concentrations may act as surfactants increasing the foaming propensity of a reactor (Kale and Singh 2016). The ammonia nitrogen level in both the influent and effluent may be viewed in Figure 5.

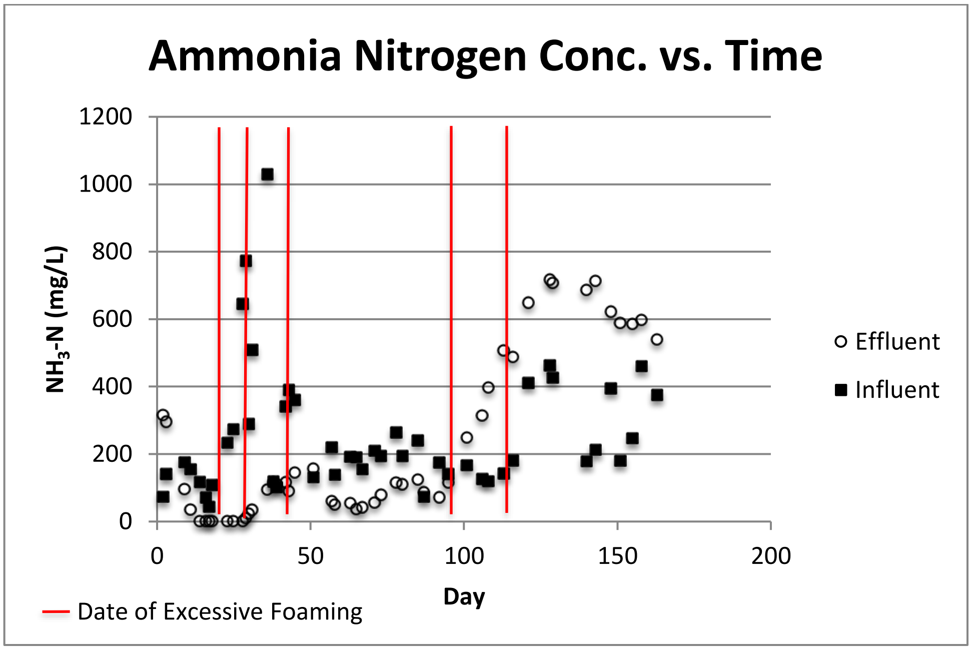

Figure 5: Reactor total alkalinity level vs. time throughout the study period.

The ammonia nitrogen concentration fluctuated in both the influent synthetic wastewater, and in the effluent leaving the reactor throughout the duration of the study. Early increases in influent ammonia nitrogen were due to an initially large retention time on the feed tank. As the wastewater sat in the tank before feeding, more of its nitrogen content was converted to ammonia nitrogen. On day 28 there was both excessive foaming and an elevated influent ammonia nitrogen concentration. This day also saw a spike in OLR of 1.0 kg/m^3•d, which would have resulted in a larger influx of ammonia nitrogen into the reactor as well. Although this shock load of ammonia nitrogen would have contributed towards the foaming event, the concentration within the reactor would have been 37.2 mg-NH_3-N/L, which is quite a low concentration and not likely the initiator of the foaming event.

On days 100 and 116, effluent ammonia nitrogen was quite high at levels of 249 and 500 mg-NH_3-N/L, respectively. This is during the period where sludge wastage was greatly reduced, meaning nitrogen began to accumulate in the system and convert to ammonia nitrogen. These concentrations were not in the range of general inhibitory levels for the overall anaerobic digestion process, however they may have been sufficient enough to contribute towards the excessive foaming events (Chen et al. 2007). The effluent ammonia nitrogen concentration did increase rapidly leading up to the excessive foaming events of days 100 and 116, however it also sat at an elevated level after these events, and no further excessive foaming events were noticed. For this reason, it may be concluded that an elevated reactor ammonia nitrogen concentration certainly contributes towards excessive foaming, but is not the factor that triggers it.

3.2 Foaming mitigation methodology

Using the experimental data collected thus far in regards to factors affecting reactor-foaming propensity, a foaming mitigation methodology was developed to apply to future operations with a similar reactor configuration. To develop this methodology, the trends in factors known to contribute towards excessive foaming events are summarized in Table 2.

Table 2: The percent-change values for each parameter leading into an excessive foaming event.

Day of Excessive Foaming Event	%-Change in Organic Loading Rate (%)	%-Change in Temperature (%)	%-Change in Total Alkalinity (%)	%-Change in Influent NH_3-N (%)	%-Change in Effluent NH_3-N (%)
17	+ 34.6%	-	+ 4.9%	- 39.4%	-
28	+ 23.4%	-	+ 3.1%	+ 136.3%	-
42	+ 30.6%	-	+ 1.2%	+ 234.3%	+ 5.5%
100	- 3.9%	+ 7.5%	+ 2.6%	+ 19.3%	+ 116.5%
116	+ 24.3%	-	- 3.4%	+ 27.5%	- 3.9%

It would appear that a shock load in OLR has the greatest influence on reactor foaming propensity. Every day of excessive foaming, aside from day 100, had a %-increase in OLR greater than 23.4% exhibited. On day 100, there was a quick increase in reactor temperature, an increase in total alkalinity concentration, and an increase in both influent and effluent ammonia nitrogen concentration. All of these factors are known to increase foaming propensity, and happened simultaneously, which is likely the reason an excessive foaming event occurred on this day. The shock increase in temperature, and the additional volatile fatty acids and biogas formation associated with it, most likely initiated the foaming event, along with the increased alkalinity and ammonia nitrogen concentrations accelerated the event.

To prevent future events from occurring, the following steps may be followed to minimize reactor foaming propensity:

1. Ensure OLR increases on a day-to-day basis are below 23.4%. A lower increase in OLR would be favourable, if possible.

2. Have cooling mechanisms present for the anaerobic digester to prevent shock increases in temperature.

3. Be cautious of shock increases in ammonia nitrogen present in feed wastewaters. This may be accomplished through maintaining a low hydraulic retention time on feed tanks containing a high pH and a nitrogen concentration that may be readily converted to ammonia nitrogen.

4. When the sludge wastage rate is reduced rapidly, ensure nitrogen and total alkalinity concentrations supplied to the reactor are lowered as well to prevent their accumulation in-situ. For full-scale application, influent wastewater could be diluted or stripped of a portion of its nitrogen and alkalinity concentrations to ensure they do not accumulate in the reactor. After sludge wastage rate increases once again, the previously removed concentrations may be slowly re-added to new feed wastewater for treatment.

4 CONCLUSIONS

Foaming events were most likely catalyzed by a shock increase greater than 20% in OLR. The excessive foaming event on day 100 is the only excessive foaming event where a shock increase in OLR was not present, however on day 100 all other factors known to increase foaming propensity increased respectively, and there was also a rapid increase in temperature of 7.5%.

A mitigation priority list was developed to prevent future foaming events during operation. Reducing OLR increases to <20% is the greatest priority, as a shock increase in OLR was found to be the likely cause for most of the excessive foaming events observed. Cooling wraps to maintain a reactor temperature of 36°C during hot summer months, ammonia nitrogen control in the effluent wastewater, and alkalinity and ammonia nitrogen control in the influent wastewater when sludge wastage rate decreases rapidly are also important to reduce reactor foaming propensity.

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