Bioresource Technology, Volume 102, Issue 12, June 2011, Pages 6637–6643

Accepted Manuscript

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Nafsika Ganidi, Sean Tyrrel, Elise Cartmell

PII: S0960-8524(11)00414-7
DOI: 10.1016/j.biortech.2011.03.057
Reference: BITE 8290

To appear in: *Bioresource Technology*

Received Date: 13 January 2011
Revised Date: 16 March 2011
Accepted Date: 17 March 2011

Please cite this article as: Ganidi, N., Tyrrel, S., Cartmell, E., The effect of organic loading rate on foam initiation during mesophilic anaerobic digestion of municipal wastewater sludge, *Bioresource Technology* (2011), doi: 10.1016/j.biortech.2011.03.057

The effect of organic loading rate on foam initiation during mesophilic anaerobic digestion of municipal wastewater sludge

Nafsika Ganidi[a,1], Sean Tyrrel[a], Elise Cartmell[a*]

[a] Cranfield Water Science Institute, School of Applied Sciences, Cranfield University, Cranfield, Beds MK43 0AL, UK

*corresponding author

Abstract

The impact of increasing organic load on anaerobic digestion foaming was studied at both full and bench scale. Organic loadings of 1.25, 2.5 and 5 kg VS m^{-3} were applied to bench-scale digesters. Foaming was monitored at a full scale digester operated in a comparable organic loading range over 15 months. The bench scale batch studies identified 2.5 kg VS m^{-3} as a critical threshold for foam initiation while 5 kg VS m^{-3} resulted in persistent foaming. Investigation of a full scale foaming event corroborated the laboratory observation that foaming may be initiated at a loading rate of $\geq$ 2.5 kg VS m^{-3}. Experimental findings on foam composition and differences in the quality characteristics between foaming and non-foaming sludges indicated that foam initiation derived from the combined effect of the liquid and gas phases inside a digester and that the solids/biomass ultimately stabilized foaming.

Keywords: foaming; anaerobic digestion; organic loading; sludge, filaments.

[1] Anglian Water Services, Thorpe Wood House, Peterborough, Cambridgeshire, PE3 6WT, UK

1 Introduction

Foaming during mesophilic anaerobic digestion (AD) has been encountered in sewage treatment works (STWs) worldwide with significant impacts on process efficiency and operational costs (Pagilla et al. 1997, Westlund et al. 1998, Barjenbruch et al. 2000, Barber 2005, Ganidi et al. 2009, Dalmau et al. 2010). A number of researchers have suggested that shock (inconsistent) loadings or digester overloading, measured as kg volatile solids per m^3 of digester per day (kg VS m^{-3} d^{-1}), can be a foaming cause (Pagilla et al. 1997, Barjenbrugh et al. 2000, Moen 2003, Barber 2005). It has been previously postulated that this may result in partial sludge degradation and associated accumulation of surface active substances, either directly found in the feed sludge such as lipids, proteins and detergents or as intermediates such as biosurfactants and fatty acids (Barjenbrugh et al. 2000, Moen 2003, Barber 2005). Shock loading, originating from a change in the composition of feed sludge, could involve a sudden qualitative change (increase in solids, surface active agents, organic content etc.) thus increasing the loading to the digester. Alternatively it could be the result of an increase in the amount of surplus activated sludge (SAS) content in the feed sludge (usually > 40% by volume) thus increasing the number of filamentous bacteria in a digester. Filamentous bacteria have previously been identified as a cause of digester foaming (Hernandez and Jenkins 1994, Westlund et al. 1998, Pagilla et al. 1997). However, experimental evidence that overloading or shock loading results in foaming is lacking and identification of a critical loading rate for foam initiation in conventional AD is unknown.

The relationship between the organic loading rate and AD foaming is investigated in this paper. Bench-scale batch digesters were operated at different organic loading rates to establish if a critical threshold for foam initiation and stabilization could be identified. Additionally, data from an extended monitoring programme of a full scale digester was used to provide complementary information.

2 Materials and Methods

2.1 Description of the full scale sewage treatment works and sample collection

A digester at a STWs in the UK (population equivalent (PE) approximately 230,000) was studied over a 15 month period. The STWs consisted of an activated sludge plant (ASP) and two primary mesophilic (35^{o}C) gas-mixed anaerobic digesters (3700 m^{3} volume each). The works received no industrial sludge imports. Retention times in the primary digesters ranged between 12-14 days. Both digesters were fitted with sensors (Charis Technology Ltd, Chatham, UK) set to raise an alarm when the foam level exceeded a set point of approximately 50 cm.

Monthly grab samples of feed and digested sludge (10 L) were collected over a 15 month period and when required prior to the batch laboratory experiments. Feed sludge was collected from a pipe outlet after the feed blending tank and before digestion. Digested sludge was collected from the overflow outlet at the top of the digester. The same digester was sampled at all times. Samples were not collected when operational problems were recorded on site that could have affected the digester's performance. The feed sludge samples had an estimated ratio of primary to SAS sludge between 6:4. Samples for the full

scale digester analysis were stored in plastic containers in a cold room at 4 ^{o}C for no more than 4 days. Samples for the batch experiments were placed in a water bath at 35 ^{o}C immediately after collection to ensure viability of bacteria.

2.2 Bench scale batch anaerobic digestion rig operation

Digestion took place in 12, 1 L, glass bottles (Fisher Scientific Ltd, Loughborough UK) placed in a thermostatically-controlled water bath (Patterson Scientific Ltd, Luton, UK) at 35 ^{o}C. The digestion bottles were sealed with rubber bungs (Fisher Scientific Ltd, Loughborough, UK) and gas was collected in glass collection columns (length: 110 cm, diameter: 5 cm) by displacement of water containing hydrochloric acid (pH <4). Magnetic stirrers (Patterson Scientific Ltd, Luton, UK) were placed underneath the water baths to keep the sludge in suspension.

Three organic loading rates (OLR), 1.25, 2.5 and 5 kg VS m^{-3}, plus a control containing only digested seed sludge were tested in triplicate during 10 day batch anaerobic digestion. Each batch experiment was repeated three times (Experiments 1, 2 and 3) to demonstrate reproducibility of the results obtained. The loading rates selected were based on the full scale digester loading rates and from information on recommended OLR found in the literature for conventional, mesophilic, anaerobic digesters, ranging from 0.5 to 7.2 kg VS m^{-3} d^{-1} (Handbooks of UK Wastewater Practice 1996, Water Pollution Control Federation 1996, Brown 2002, Gerardi 2003, Harrison et al. 2004, Bolzonella et al. 2005, Braguglia et al. 2007, Zupančič et al. 2008, Cartmell and Chinaglia 2009). The proportion of feed to digested sludge varied for each batch experiment as it was based on the volatile solids content of the feed sludge in order to achieve the required loading. The height of foam in

the bottles was measured daily and foam was subsequently destroyed daily by stirring. On Day 3 of batch digestion, one digestion bottle per loading rate was removed from the water bath for sludge and foam analyses. On Day 10, the digestion was stopped, when gas production was < 30 $cm^3 d^{-1}$ and similarly sludge and foam samples were collected for analysis from the remaining bottles.

2.3 Foaming test apparatus and methodology completed on the full scale digester samples

The foaming tests were carried out on 1 L feed and digested sludge and sludge-centrate samples, collected from the full scale STWs as described in section 2.1. Sludge -centrate samples were obtained by centrifuging either the feed (feed-centrate) or digested sludge (digested-centrate) samples at 2000 g for 15 minutes and subsequently collecting the supernatant. The foaming potential was determined by measuring the foam height after aeration at 0.5 L $minute^{-1}$ for 10 minutes (NG et al. 1977, Morey et al. 1999, Desphande and Barigou 2000, Desphande and Barigou 2001, Dedhia et al. 2004, Nakajima and Mishima 2005). The apparatus comprised of a column (length: 1 m, diameter: 5.2 cm) with a plastic, fine-bubble diffuser placed at the bottom. Foaming propensity and foam stability were determined during the foaming tests. Foaming propensity was calculated based on the amount of foam generated from a sample after aeration normalized over the solids content of the sample in order to allow comparison of the foaming potential of different samples (Equation 1). Foam stability was monitored indirectly by measuring the foam height 1 hour after aeration ceased (Equation 2). All measurements were carried out in triplicate.

2.4 Analytical methods

Total solids (TS), volatile solids (VS) and alkalinity determination were carried out according to the Standard Methods for the Examination of Water and Wastewater (APHA, Greenberg et al. 1998). Solid-free sludge samples were obtained after centrifugation at 2000 g for 15 minutes and filtration (0.45 μm glass-fiber filter papers, Whatman, Maidstone, UK) and were analyzed for alkalinity by titration of 0.02 M hydrochloric acid. Total volatile fatty acids (tVFAs), including acetic, propionic, n- and iso- butyric, n- and iso-valeric acid, were determined in sludge samples acidified with concentrated sulphuric acid to stop microbial activity and stored at −20 ^{o}C until analysis. Filtration through 0.45 μm glass-fiber filter papers was carried out prior to analysis by high performance liquid chromatography (HPLC) (Shimadzu VP Series, Shimadzu, UK) using a Bio-Rad fermentation column (Bio-Rad, Hercules, CA, USA) for separation of VFAs. The column temperature was set at 65 ^{o}C and 1 mM sulphuric acid was used as mobile phase at 0.8 ml minute^{-1} flow. Volatile fatty acid detection was performed by a UV detector at 208 nm (Galanos et al. 1995, Sanford et al. 2002, Parawira et al. 2004). Soluble COD (SCOD) was determined in samples after centrifugation at 2000 g for 15 minutes and filtration by a COD kit (VWR, Lutterworth, UK). The absorbance was measured by a Spectroquant Nova 60 Spectrophotometer (VWR, Lutterworth, UK). Dissolved organic carbon (DOC) was determined with a Shimadzu TOC – 5000A analyzer in samples after centrifugation and filtration as described previously. Filamentous bacteria were identified according to Eikelboom (2000). Gram stains (HD Supplies, Aylesbury, UK) with safranin as the counter stain and Neisser stains (Fisher Scientific, UK) were used for staining of filaments in

sludge. Light microscopy (BHB, Olympus) was then used to identify the species according to a scale from 1 to 5, 1 being the lowest and 5 being the highest, was used to describe the abundance. Analysis of foam samples was carried out based on the methods as described above.

2.5 Statistical methods

Descriptive statistics were carried out for all data involving the calculation of mean values, standard deviations and standard errors. Further statistical analysis of the data involved examination of the normality of the data and subsequently one-way analysis of variance (ANOVA) using Statistica.

3 Results and Discussion

3.1 Investigation of the effect of organic loading on foaming at bench scale

Persistent, recurring foaming was recorded from the highest loading tested (5 kg VS m^{-3}), in all three repeated bench scale batch experiments (Experiments 1-3) with foam volumes varying from 1.1 % to 18.9 % of the total volume of the digestion bottle. The 2.5 kg VS m^{-3} loading did not consistently produce foam during the digestion period with foam volumes varying from 0% to 3.8% of the total volume of the digestion bottle during all three experiments. The daily foam production is illustrated in Figure 1. It is important to highlight that foam was destroyed daily by stirring after each recording and reappeared within a day. No foaming was recorded in either the control or the 1.25 kg VS m^{-3} loading digestion bottles during batch digestion any of the three experiments.

Additional information on gas and methane production, solids reduction, tVFAs and alkalinity for the three experiments showed that the digestion process was not inhibited at any of the loading rates tested. The highest cumulative gas production was recorded from the 5 kg VS m^{-3} loading (1445 – 1959 mL biogas) with cumulative gas production from the 1.25 and 2.5 kg VS m^{-3} loading at 91 – 495 mL and 402 – 996 mL biogas, compared to a range of 131 – 399 mL in the control. The 5 kg VS m^{-3} loading consistently produced a higher methane content (52 – 67 %) than the 1.25 (35 % – 56 %) and 2.5 kg VS m^{-3} (38 – 58 %) treatments during all three experiments. The tVFAs in digested sludge at the end of batch digestion did not exceed 28 mg L^{-1} in any of the treatments. Alkalinity values from all three loadings ranged from 2950 to 3325 mg L^{-1}. There was a statistically significant difference for both SCOD and DOC values (SCOD P=0.004, DOC P=0.002, a=95 %) in digested sludge at the end of batch digestion (Day 10) with values in sludge from the 5 kg VS m^{-3} loading significantly higher than those from the 1.25 kg VS m^{-3} loading. Yet, the same was not observed between the 1.25 and 2.5 kg VS m^{-3} loading. The TS content in the foam samples (5.7 – 7.5 %) (Table 1) was significantly higher than that in sludge (2.2 – 4.5 %). On the contrary, VS did not vary considerably between sludge (49 – 77 %) and foam (51 – 66 %).

The tVFAs values in the foam varied from 1 to 65 mg L^{-1} during the batch digestion period of all three experiments. The individual VFAs observed in the foam and sludge were acetic, n-butyric and iso-valeric acids whilst no iso-butyric and n-valeric acids were present in either sludge or foam during the experiments. This indicated that there was no preferential partitioning of individual VFAs into the foam. Dissolved organics concentrations in foam

ranged from 5 to 493 mg L^{-1} on Days 3 and 10 during the three experiments and generally increased on Day 10 compared to Day 3.

Three filament species were identified in sludge and foam samples in this work, *Microthrix*, *N.limicola I* and *N.limicola III*, as shown in Table 2. The filament abundance was overall moderate as it did not exceed a filament index (FI) of 3. After the 10-day digestion period *N.limicola I* was no longer present in sludge or foam during experiment 1 but *Microthrix* and *N.limicola III* were still present in sludge and foam samples.

3.2 Investigation of a foaming event at full scale

The studied full scale digester had no foaming issues for over a year prior to commencement of the work presented here. During the monitoring period a foaming event was recorded in the digester between two sampling occasions (26.03.08 and 8.04.08). The foam disappeared after 3-4 days and no antifoam was dosed during the event due to the nature and duration of foaming.

The OLR of the full scale digesters varied from 1.44 to 2.84 kg VS m^{-3} d^{-1} during the 15-month monitoring period with an average value of 2.25 kg VS m^{-3} d^{-1} (SD: 0.43 kg VS m^{-3} d^{-1}). The foaming incident followed loadings of 2.81 and 2.68 kg VS m^{-3} d^{-1} on 14.03.08 and 26.03.08, respectively, as seen in Figure 2. The full-scale digester achieved 37 % TS reduction and 42 % VS reduction only on 5.11.07 (Figure 3) with all the other values being below that range which was attributed to the effect of dilute feed. The VS reduction ranged from 11 % to 42 % during the monitoring period with an average value of 28 % (±SD:8%). All tVFAs values in the digester ranged from 0 to 83 mg L^{-1}. In addition, all alkalinity

values (average of 3860 mg L^{-1}, SD: 868 mg L^{-1}) were within the recommended range (2000-5000 mg L^{-1}) (Handbooks of UK Wastewater Practice 1996) apart from one occasion (8.04.08) right after the foaming incident with alkalinity in digested sludge observed at 5780 mg L^{-1}. The DOC concentrations were variable with average values of 1175 mg L^{-1} (SD: 319 mg L^{-1}) and 282 mg L^{-1} (SD: 87 mg L^{-1}) for feed and digested sludge, respectively, over the monitoring period. The DOC in digested sludge samples increased in the period between 14.03.08 and 8.04.08 compared to values obtained in previous sampling occasions and the increase in DOC coincided with the foaming event with the maximum DOC value (440 mg L^{-1}) recorded just after the foaming incident.

Feed sludge samples and feed-centrate samples showed a variable foaming propensity during the monitoring period (Table 3). The high foaming propensity values of feed and feed-centrate recorded on 9.07.07, 14.03.08 and 26.03.08 did not have an impact on digested sludge foaming propensity. It was noticed, however, that the two highest foaming propensity values were found in the feed-centrate samples before the foaming incident was recorded at the full scale but not in the whole sludge sample. Digested sludge foaming propensity was consistently much lower than digested-centrate foaming propensity during the monitoring period. Foam stability was observed on two occasions in the feed sludge sample only (9.07.07, 11.76±1.55 cm^3 foam mL^{-1} air min^{-1}, 5.11.07, 0.27±0.03 cm^3 foam mL^{-1} air min^{-1}). However, this had no impact on the digested sludge foam stability and was not linked with foaming observed on the full scale digester.

Five filament species were found in the full scale digester, including *N.limicola I* and *III*, *Microthrix*, *0041*, *0581* (Figure 4). The overall abundance did not exceed a filament index

of 3. In detail, the species 0041 and 0581 had the highest abundance during the monitoring period with FI between 1- 3 and 1-2.5, respectively. *Microthrix* abundance did not exceed a FI of 1.5 during the monitoring period. Before the foaming event was recorded at full scale, the abundance of *0041* species increased from 2 to 3 on the filament index scale (26.03.08). Yet, digested sludge contained only one other species, *N.limicola III,* at low abundance (FI<1) just before the foaming event.

3.3 Organic loading as a foaming cause

This work attempted to identify a critical organic loading threshold for foam initiation and stabilization during conventional mesophilic AD. It is appreciated that each digester could in practice operate with its own critical threshold (Dalmau et al. 2010). However, the bench scale batch anaerobic digestion experiments on sludge obtained from a non-foaming full scale digester identified the 2.5 kg VS m^{-3} loading as critical for foam initiation with foam lasting between 1 and 4 days and the 5 kg VS m^{-3} loading resulting in persistent foaming. The bench scale findings also demonstrated that sludge obtained from a non-foaming full scale digester has the potential to foam under critical conditions (increased organic loadings) at bench scale.

Overloading/shock loading of digesters can result in partial sludge degradation and associated accumulation of surface active substances, either directly found in the feed sludge such as lipids, proteins and detergents or as intermediates such as biosurfactants and fatty acids (VFAs) often leading to digester instability and subsequently foaming (Ross and Ellis 1992, Pagilla et al. 1997, Westlund et al. 1998, Barjenbrugh et al. 2000, Moen 2003,

Barber 2005). Standard monitoring and analysis during the bench scale batch experiments carried out in this work (gas and methane production, solids reduction, tVFAs and alkalinity) showed no clear evidence of partial sludge degradation and therefore unstable digestion due to higher organic loadings. Gas and methane production increased with increasing organic loading with the 5 kg VS m^{-3} loading consistently producing more methane (52 – 67 %) than the 1.25 (35 % – 56 %) and 2.5 kg VS m^{-3} (38 – 58 %) treatments. Total VFAs in digested sludge at the end of batch digestion did not exceed 28 mg L^{-1} from all loadings and all three batch experiments (upper recommended limit for AD:300 mg L^{-1}) and alkalinity values ranged from 2950 to 3325 mg L^{-1}. Further determination of SCOD and DOC in digested sludges obtained at the end of the batch experiments showed a statistically significant difference only in sludges between the 1.25 (non-foaming) and 5 kg VS m^{-3} d^{-1} (foaming) loading. Data from the long term monitoring of the performance of the full scale digester were in accordance with the bench scale findings supporting the theory that foaming can occur when no signs of inhibition or imbalance are observed. An increase in DOC (440 mg L^{-1}, average: 282 mg L^{-1}) and alkalinity values (5780 mg L^{-1}, average: 3860 mg L^{-1}) followed the foaming incident but there was no VFAs accumulation in the digester or other clear sign of digestion inhibition. The average organic loading to the digester during the monitoring period was 2.25±0.43 kg VS m^{-3} d^{-1} with foaming following loadings of 2.81 and 2.68 kg VS m^{-3} d^{-1}, verifying the bench scale findings that foaming may be initiated at loading rates ≥2.5 kg VS m^{-3}. In addition, these findings indicated that typical monitoring of AD involving gas and methane production, solids reduction and tVFAs is not adequate to identify differences between foaming and non-foaming digesting sludge.

3.4 Foams as 3-phase systems

To understand the key components of foam and the mechanisms of foam generation in AD, the theory of Davenport and Curtis (2002), examining foam as a 3-phase system with gas-liquid-solid interactions, has been taken into consideration.

3.4.1 Gas phase

The gas phase is always present in AD in the form of biogas production with digester gas mixing systems having an increased gas content. Gas production alone could not have resulted in foaming as the presence of surface active agents is necessary for foam initiation (Vardar-Sukan 1998, Glaser et al. 2007). However, the higher gas production of the 5 kg VS m^{-3} loading compared to the 2.5 kg VS m^{-3} loading could have contributed to foaming as increased gas rates can increase foam formation as demonstrated by Varley et al. (2004).

3.4.2 Liquid phase

Research has shown that the onset of foaming in liquids is due to the presence of surfactants and biosurfactants, abundant in wastewater and sludge. They have both hydrophobic and hydrophilic properties and tend to accumulate at air – liquid interfaces increasing surface activity. When gas is introduced into solution, a thin liquid film is formed around the gas bubbles as they reach the air – liquid interface preventing them from bursting (Hug 2006, Ganidi 2009). The foaming propensity tests carried out in feed and digested sludge and their centrate samples collected from the full scale digester showed that surfactants were consistently present in all samples examined with digested – centrate demonstrating the highest foaming propensity. The latter did not seem to be affected by the

feed and feed-centrate foaming propensity according to the experimental findings (Table 3) indicating that the surfactants in the digested-centrate responsible for foaming under aeration were produced during anaerobic digestion. Additionally, the liquid phase of the full scale digester contained significant amounts of surfactants during the monitoring period, yet, the foaming potential was decreased in the presence of solids as foaming propensity of the digested sludge samples was considerably lower than that of the centrates in all cases (average foaming propensity of digested sludge: 0.4 mm g^{-1} TS, average foaming propensity of centrate: 31.7 mm g^{-1} TS), potentially due to interactions between solid particles and the surfactants. The literature suggests that in complex surfactant systems, such as sludge, which contain a number of surfactants, the foaming potential could be enhanced or reduced depending on the surfactant – surfactant and particle - surfactant interactions (Glaser et al. 2007, Eisner et al. 2007). Additionally, increases in temperature in liquids containing surfactants result in increased surface activity (lower surface tension) and enhanced foaming potential (Barber 2005). Therefore, the behavior of the surfactants in the full scale digester and their impact on foam initiation is dependent on the effect of mesophilic temperatures and surfactant – surfactant, particle - surfactant interactions. In order to gain a better understanding of foam creation and stabilization, the liquid phase of foams generated at bench scale was analyzed for DOC and tVFAs. The amount of tVFAs found in foam on both Day 3 and Day 10 of batch digestion was relatively low (1 – 65 mg L^{-1}) and concentrations found in the corresponding sludge samples were 0 – 266 mg L^{-1} on both Day 3 and Day 10 with no consistent evidence of VFAs partitioning in the foam. Thus, it was considered that VFAs were potentially not an essential component of AD foams. However, hydrophobic compounds present in the DOC foam concentration (5 to

493 mg L^{-1} on Day 3 and Day 10) could have contributed to the generation and perhaps stabilization of foaming by accumulating at air interfaces and preventing air bubbles from bursting.

3.4.3 Solid phase

Recent studies have shown that wastewater foam stabilization is mainly due to the filamentous *Gordonia* and *M.parvicella* but there is evidence suggesting that non filamentous mycolic-acid containing microorganisms, of which specific species have not yet been identified, also act as stabilizing agents (Hug 2006, Heard et al. 2008). Five filamentous species were found in sludge in the full scale digester, of which no reference has been found in the literature for the four species, *N.limicola I* and *III*, 0041 and 0581 in relation to foaming. Investigation of the contribution of *Microthrix* to foam stabilization during bench scale batch digestion in this work showed insignificant partitioning to foam as the filament abundance was either the same or higher by only one unit of the filament index in foam compared to sludge. Consequently, foam stabilization due to the presence of filamentous bacteria was not clearly seen during this work. It is possible that the high solids content in the foam could have been attributed to the presence of mycolic acid containing microorganisms, which in addition to the filamentous bacteria stabilized the foam at bench scale.

Overall, foam initiation derives from the liquid phase when the gas phase is present and the solid phase can enhance and stabilize foaming. Subsequently, it can be concluded that although increased organic loading has been identified here as a foaming cause, it is believed that the effect of increased organic loading on the digestion process and

specifically on the liquid fraction of sludge (measured here as increased DOC) initiated foaming.

4 Conclusions

- An organic loading of 2.5 kg VS m^{-3} was identified as a critical organic loading threshold for foam initiation for sludge obtained from a non-foaming full scale digester while 5 kg VS m^{-3} resulted in persistent foaming.
- Survival of filamentous microorganisms during AD was evident at full scale and five species were identified (*Microthrix, N.limicola I & III,* 0041, 0581) with an overall abundance not exceeding a filament index of 3.
- *Microthrix, N.limicola I* and *III* were present in sludge and foam samples during bench scale batch digestion. However, their contribution to foaming at bench scale was considered insignificant.

Acknowledgements

The authors gratefully acknowledge funding for this work from Anglian Water, Northumbrian Water, Severn Trent Water, Thames Water, United Utilities and Yorkshire Water.

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FIGURE LEGENDS

Figure 1: Daily foam production as a percentage of the volume of the digestion bottle (±SD) during batch anaerobic digestion of Experiments 1, 2 and 3.

Figure 2: Volatile solids loading (kg VS m^{-3} d^{-1} ±SD) of the full scale digester

Figure 3: Total and volatile solids reduction (% ±SD) for the full scale digester

Figure 4: Filamentous bacteria abundance in digested sludge of the full scale digester

$$foaming\ \ propensity = \frac{mm\ \ of\ \ foam\ \ after\ \ aeration}{gram\ \ total\ \ solids}$$

Equation 1: Foaming propensity in mm g^{-1}

$$foam\ \ stability = \frac{foam\ \ volume\ \ after\ \ 1hr\ \ settling,\ \ cm^3}{air\ \ flow\ \ rate,\ \ ml.\min^{-1}}$$

Equation 2: Foam stability in $cm^3\ ml^{-1}\ min^{-1}$

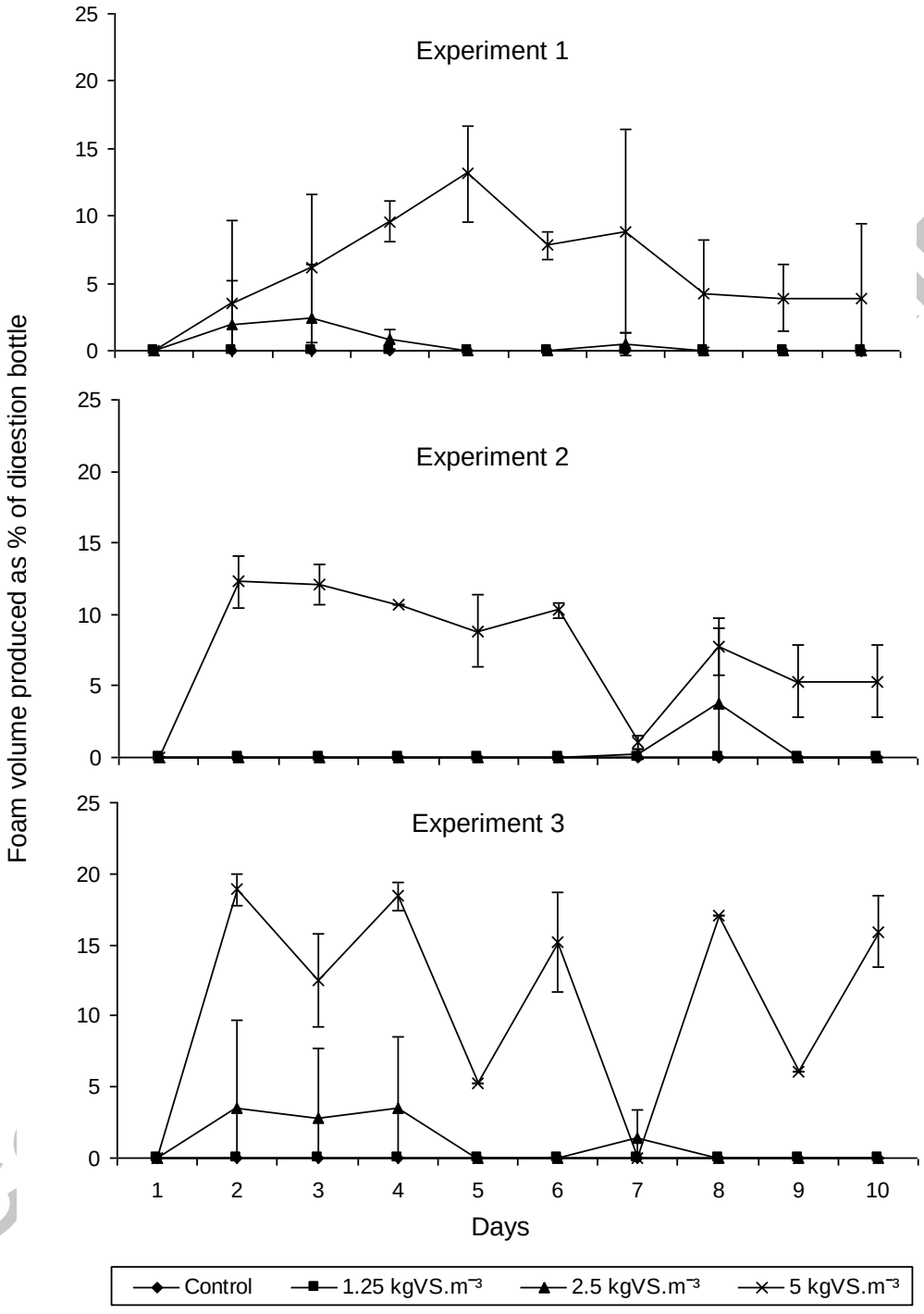

Figure 1: Daily foam production as a percentage of the volume of the digestion bottle (±SD) during batch anaerobic digestion of Experiments 1, 2 and 3.

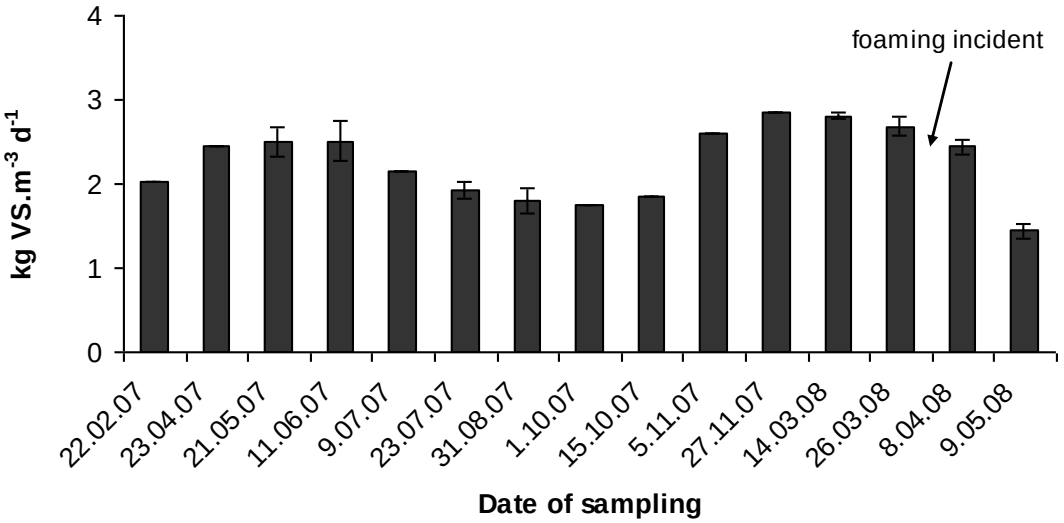

Figure 2: Volatile solids loading (kg VS m^{-3} d^{-1} ±SD) of the full scale digester

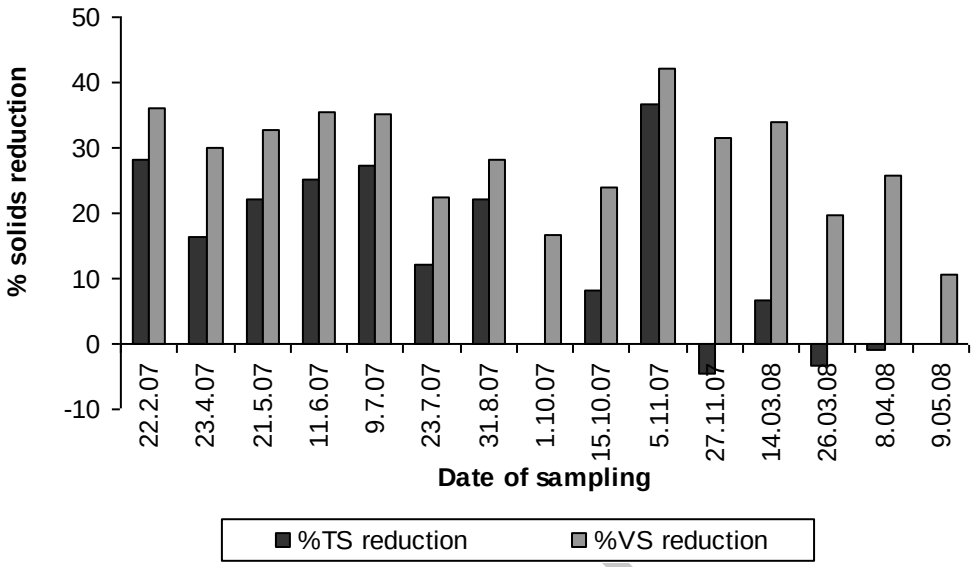

Figure 3: Total and volatile solids reduction (% ±SD) for the full scale digester

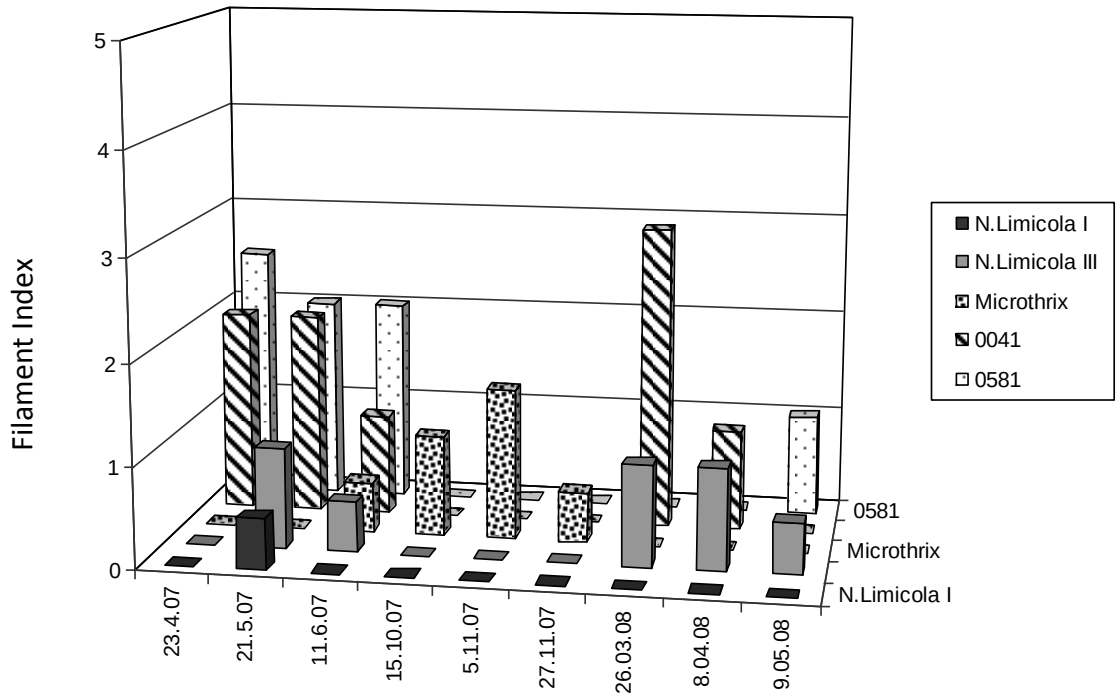

Figure 4: Filamentous bacteria abundance in digested sludge of the full scale digester

Table 1: Quality characteristics of foam samples from the 5 kg VS m^{-3} loading

	Experiment 1	*Experiment 2*	*Experiment 3*
TS (%)			
Day 3	5.7[a]	7.4±0.3	6.3±0.4
Day 10	6.0[a]	7.0±0.0	7.5±0.3
VS (%)			
Day 3	65.7[a]	61.5±0.4	59.3±3.5
Day 10	66.2[a]	63.4±0.1	51.4±1.4
tVFAs (mg L^{-1})			
Day 3	6.0[a]	3.1±4.5	29.0±18.4
Day 10	64.6[a]	1.3±2.2	16.7±0.6
DOC (mg L^{-1})			
Day 3	182.0±0.1	5.0[a]	328.0±23.9
Day 10	324.0±12.8	273.0[a]	493.0±15.7

([a]): Single analysis due to sample volume limitations

± : Standard deviation

Table 2: Filament index in sludge and foam samples during bench scale batch digestion

		Microthrix		*N.limicola I*		*N.limicola III*	
		Day 3	Day 10	Day 3	Day 10	Day 3	Day 10
Experiment 1	non foaming sludge (*control*)	1	0.5	-	-	-	-
	foaming sludge (*5 kg VS.m^{-3} loading*)	1	1	1	-	1	0.5
	foam (*5 kg VS.m^{-3} loading*)	3	2	1	-	-	1
Experiment 2	non foaming sludge (*control*)	1.5	1	-	-	-	-
	foaming sludge (*5 kg VS.m^{-3} loading*)	1	1	-	-	0.5	0.5
	foam (*5 kg VS.m^{-3} loading*)	2	1	-	-	-	-
Experiment 3	non foaming sludge (*control*)	0.5	0.5	-	-	-	-
	foaming sludge (*5 kg VS.m^{-3} loading*)	0.5	-	-	-	-	-
	foam (*5 kg VS.m^{-3} loading*)	0.5	0.5	-	-	-	-

Table 3: Foaming propensity (mm of foam per gram TS) of feed and digested sludge samples and their centrates obtained from the full scale digester over the 15 month monitoring period

Date	**Feed**	**Digested**	**Feed-centrate**	**Digested-centrate**
9.07.07	21.7	0.1	1.7	39.3
1.10.07	1.1	0.4	2.0	8.3
15.10.07	2.7	0.4	0.0	63.5
5.11.07	3.6	0.6	0.0	43.3
27.11.07	1.6	0.2	5.5	45.0
14.03.08	1.3	0.0	34.6	8.7
26.03.08	0.2	0.2	45.7	21.3
8.04.08[a]	0.8	0.5	3.6	12.6
9.05.08	1.1	0.9	17.5	43.7
mean	***3.8***	***0.4***	***12.3***	***31.7***
minimum	***0.2***	***0.0***	***0.0***	***8.3***
maximum	***21.7***	***0.9***	***45.7***	***63.5***
SD	***6.8***	***0.3***	***16.9***	***19.6***

[a]: Sampling followed the foaming incident