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Impact of low loading on digestion of the mechanically-separated organic fraction of municipal solid waste

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Abstract

Changing waste management practice, introduction of new technologies, and population demographics and behaviour will impact on both quantity and composition of future waste streams. Laboratory-scale anaerobic digestion of the mechanically-separated organic fraction of municipal solid waste (ms-OFMSW) was carried out at relatively low organic loading rates (OLR), and results analysed using an energy modelling tool. Thermophilic operation with water addition and liquor recycle was compared to co-digestion with dilution water replaced by sewage sludge digestate (SSD); thermophilic and mesophilic mono-digestion were also tested at low OLR. All thermophilic conditions showed stable operation, with specific methane production (SMP) from 0.203-0.296 m^3 CH_4 kg^{-1} volatile solids (VS). SSD addition increased biogas production by ~20% and there was evidence of further hydrolysis and degradation of the SSD. Long-term operation at 1 kg VS m^{-3} day^{-1} had no adverse effect except in mesophilic conditions where SMP was lower at 0.256 m^3 CH_4 kg^{-1} VS and stability was reduced, especially during OLR increases. This was probably due to low total ammonia nitrogen, which stabilised at ~0.2 g N kg^{-1} and limited the buffering capacity. Energy analysis showed thermophilic operation at OLR 2 g VS L^{-1} day^{-1} gave 42% of the theoretical methane potential and 38% of the higher heating value, reducing to 37% and 34% respectively in mesophilic conditions. Scenario modelling indicated that under low ms-OFMSW load even an energy-depleted co-substrate such as SSD could contribute to the energy balance, and would be a better diluent than water due to its nutrient and buffering capacity.

Keywords: OFMSW, mesophilic, thermophilic, sewage sludge digestate, ammonia, energy modelling

1 Introduction

Anaerobic digestion (AD) of the organic fraction of municipal solid waste (OFMSW) after mechanical separation is a well-established technology, and its performance characteristics and limitations are known both from long-term laboratory and pilot-scale research (Mata Alvarez, 2002; Hartmann and Ahring, 2006); and from studies of full-scale plant (Montejo et al., 2013; Romero-Güiza et al., 2014; Colón et al., 2017; Barati et al., 2017). By 2014 there were an estimated 244 AD plants in operation or under construction in Europe for which OFMSW made up a significant proportion of the feedstock (De Baere and Mattheeuws, 2013). These plants are of many different types, and have evolved together with technical and engineering developments to accommodate the range of collection and separation systems used in preparation of this waste feedstock. Despite this extensive experience, there are circumstances in which the process may operate under loading conditions that lower than those it was designed for, or otherwise non-optimal. Lower loadings of course occur as a transient state during start-up, and studies have looked at the best strategies to address this (Bolzonella et al., 2003). A more important case is where the plant is oversized and the organic loading rate (OLR) is low due to a shortfall in the anticipated sources of waste: while such information is often commercially confidential, examination of the available data on digester sizes, input waste tonnages and combined heat and power (CHP) generation capacity suggests that not all plants are working at full capacity. This may be due to initial over-sizing, or to successful initiatives to increase recycling, of the type currently being adopted worldwide in a drive towards greater sustainability. While separation of recyclable materials may change the proportion of non-degradable components in the waste, however, there is evidence that it does not greatly alter the suitability of this residual stream as an AD feedstock (Waite, 2013; Fonoll et al, 2016).

A further factor that is likely to have an increasing impact in future is the adoption of alternative technologies for recovery of materials and energy from the general waste stream, which may leave reduced volumes of residual waste for digestion. These include waste-based biorefinery processes to recover selected fractions for conversion into a range of downstream building blocks, including alcohols (Farmanbordar, 2018; Mahmoodi et al., 2018), volatile fatty acids (Cavinato et al., 2017; Aguilar et al., 2013), and sugars and high value products (Vaurs et al., 2018; Sadhukhan et al., 2016). Further sources of competition for wastes may include thermal processing technologies for recovery of energy and products through gasification, pyrolysis and hydrothermal carbonisation (Yang et al., 2018; Dong et al., 2018). While many of these processes are still under development, and not all will make the transition to full-scale operation, it is clear there is potential for significant future competition for wastes. AD technologies are likely to retain a place at the core of such biorefineries for post-processing of residues; but, in addition to reduced tonnages, the characteristics of these residues will be significantly different from those of traditional mechanically-separated OFMSW (ms-OFMSW).

In some cases, a shortfall in ms-OFMSW may be addressed by seeking opportunities for co-digestion with complementary feedstocks such as wet wastes. Municipal wastewater biosolids have long been recognised as a promising co-substrate, and have been extensively studied (Hamzani et al., 1998; Sosnowski et al., 2003; Bolzonella et al., 2006; Silvestre et al., 2015). Few or no studies appear to have looked at co-digestion with sewage sludge digestate (SSD), however, probably because the majority of the readily degradable fraction is already likely to have been converted into biogas. This co-substrate may, however, be useful in complementing the nutrient profile of the original feedstock, which is often cited as a reason for co-digestion (Tyagi et al., 2018).

The current study aimed to consider a number of scenarios where ms-OFMSW digestion is carried out at relatively low OLR. One objective was to provide a baseline for thermophilic digestion of a particular ms-OFMSW feedstock, for comparison with alternative energy recovery options including integrated pyrolysis and anaerobic digestion (Yang et al., 2018b). Another was to simulate the effect of a lower OLR, such as might occur in an existing plant with a long-term shortfall in waste feedstock. The digester operating mode was based upon that used in a number of full-scale UK plants which run at a moderate OLR of around 2 kg volatile solids (VS) m^{-3} day^{-1}. Solids and liquid retention times in these plants are uncoupled by digestate separation and solids wasting, with solids typically retained for around 20-30 days. Input to the digesters normally consists of around 14-15% OFMSW, 35-36% fresh water and 50% recycled digestate on a wet weight basis. This baseline scenario was compared with one where the waste input is reduced to 1 kg VS m^{-3} day^{-1} but the total input tonnage and hydraulic retention time (HRT) is maintained by addition of more water. For the lower OLR, the study also looked at substitution of the added fresh water with SSD to provide additional buffering and input of inoculum, plus some residual biogas potential. The trials were run under thermophilic conditions, but the lower OLR without SSD was also run at a mesophilic temperature to provide comparative data on the energy production potential. The impact of the different scenarios on the energy balance was considered using the ADAT modelling tool (BORRG, N.D). The results provide useful insights for operators of full-scale plant facing current or potential changes in ms-OFMSW feedstock availability, and on benefits that might arise from substrate blending with digestate from municipal wastewater biosolids treatment.

2 Materials and methods

2.1 Feedstock

Mechanically-separated OFMSW was obtained from the Bursom Recycling Centre, Leicester (Biffa Plc, UK). The residual mixed waste entering this plant is processed in a ball mill and then separated by a drum screen into two size fractions of 0-40 mm and 40-80 mm. The 0-40 mm fraction goes through a slotted flip-flop screen to remove excess water and then through a 5 mm grid. The material is then placed in closed containers for transport to the Wanlip AD plant (Biffa Plc, UK). Two batches, each of ~300 kg, of this bulk material were passed through a 10 mm screen to remove any large non-organic contaminants that could damage the smaller-scale digestion equipment. The <10 mm fraction of the processed OFMSW was stored in 2-kg plastic bags at approximately -20 ^{o}C, and thawed for 24 hours at room temperature before use. Once defrosted, the OFMSW was maintained at 4 ^{o}C and used within 5 days.

2.2 Digestion experiments

The trial used four continuous stirred-tank reactor (CSTR) digesters, each with an internal diameter of 0.32 m, a height of 0.55 m and a working volume of 35 L. Each digester was fitted with top and bottom flange plates, and was mixed by a mechanical stirrer connected through a gas-seal draught tube in the top plate connected to a geared motor operating at 35 rpm. Fresh feed was added via a port in the top plate, and digestate removed from the bottom via a drain tube. Digesters were maintained at 36 ± 1 °C (mesophilic) or 55 ± 1 °C (thermophilic) by an internal heating coil. Biogas production from each digester was measured continuously using a tipping-bucket gas flow meter as described in Walker et al. (2009).

Experimental conditions are summarised in Table 1. The experimental period was divided into two stages as described below.

Stage 1. The trial used 2 digesters (T1 and T2) which had previously been operated thermophilically (55 °C) for a period of 345 days treating source segregated domestic food waste with side-stream ammonia removal at an OLR of 2 g VS L^{-1} (Zhang et al., 2017). On day 0 the digestates from T1 and T2 were removed, mixed to ensure homogeneity and replaced in the digesters, then left without feeding for 12 days to allow degradation of residual feedstock. Feeding of T1 and T2 on OFMSW as the sole substrate started on day 13 at an OLR of 0.5 kg VS m^{-3} day^{-1} and was increased to 1 kg VS m^{-3} day^{-1} on day 16. From day 71 onwards the operating mode was changed to include liquid addition, in accordance with typical operational practice at a number of large-scale plants in the UK. To simulate this, each day 1.666 kg of digestate was removed and the liquid and solids fractions were separated using a 1 mm nylon mesh sieve. The separated solids were discarded, giving a digester solids retention time (SRT) of 21 days. The digester received daily a wet weight of fresh OFMSW sufficient to give an OLR of 1 g VS L^{-1} day^{-1}, and 715 g of SSD from a mesophilic AD plant treating municipal wastewater biosolids (Millbrook, Southampton UK). Approximately 833 g of the separated digestate liquor was then returned to the digester to maintain the working volume, giving a nominal HRT of 42 days. T1 and T2 both received the same feed, and operated at a combined OLR (OFMSW + SSD) of ~1.7 kg VS m^{-3} day^{-1}.

Stage 2. In this part of the work the digesters were operated to simulate low loadings without co-digestion with SSD. On day 236 the addition of SSD to T1 and T2 as part of the feed was discontinued and 715 g of tap water substituted, reducing the OLR to 1 kg VS m^{-3} day^{-1}.

From day 385 the OLR was gradually increased over a 10-day period to 2.0 g VS L^{-1} day^{-1}, by increasing the amount of OFMSW added and decreasing the quantity of tap water proportionally. Feeding continued at this loading until the end of the experimental period on day 525.

A second pair of digesters (M1 and M2) was brought into operation on day 243 and inoculated with digestate taken from the Millbrook AD plant. These were operated mesophilically (37 ^{o}C) at a HRT of 42 days and SRT of 21 days using the same solids/liquor separation method as for T1 and T2, with the aim of providing comparative data on thermophilic and mesophilic operation with the same feedstock and operating mode. From day 244 onwards M1 and M2 were fed on OFMSW, recycled liquor and tap water at an OLR of 1.0 kg VS m^{-3} day^{-1}. Attempts to increase the OLR after day 385, as in T1 and T2, led to signs of instability. The loading on M1 and M2 thus had to be reduced, then was gradually restored to 1.0 kg VS m^{-3} day^{-1} from day 479 until the end of the experimental period.

Trace element (TE) solutions were added to the digesters on two separate occasions to give the following additional concentrations in the digester (mg L^{-1}): Al 0.1, B 1.0, Co 1.0, Cu 0.1, Fe 5.0, Mn 1.0, Mo 0.2, Ni 1.0, Se 0.2, W 0.2, Zn 0.2 (Banks et al., 2012).

2.3 Analytical methods

Total solids (TS) and VS were measured according to Standard Methods 2540 G (APHA, 2005). pH was determined using a Jenway 3010 meter (Bibby Scientific Ltd, UK) calibrated in buffers at pH 4.0, 7.0 and 9.2 (Fisher Scientific, UK). Alkalinity was measured by titration with 0.25N H_2SO_4 to endpoints of pH 5.75 and 4.3 (Ripley et al., 1986). Total Kjeldahl nitrogen (TKN) and total ammoniacal nitrogen (TAN) were determined using a Kjeltech block digestion and Büchi steam distillation unit according to the manufacturers' instructions (Foss Ltd, Warrington, UK). Crude protein content was calculated by multiplying the difference between TKN and TAN by 6.25 (Hansen et al., 1998). Samples for volatile fatty acid (VFA) analysis were prepared by centrifuging at 13600 *g* for 10 min and acidifying the centrifugate with 10% (v/v) formic acid. VFA in the supernatant was measured by gas chromatography (model GC-2010, Shimazdu, Tokyo, Japan), using a flame ionization detector and an FFAP capillary column (SGE Europe Ltd, UK) with helium as the carrier gas. Biogas composition was analysed using a Varian CP 3800 gas chromatograph with a gas sampling loop, with argon as the carrier gas. The GC was calibrated using a standard gas containing 35% CO_2 and 65% CH_4 (BOC, Guildford, UK). Elemental composition and higher heating values (HHV) were analysed as reported by Yang et al. (2018).

Digestate parameters such as TS, VS, VFA, TAN and alkalinity, as well as biogas composition, were analysed once per week. Gas volumes were measured using a weight-based gasometer and are reported corrected to standard temperature and pressure (STP) of 0 ^{o}C, 101.325 kPa as described in Walker et al. (2009).

The theoretical HHV was calculated using the Dulong equation according to IFRF (2017). Theoretical methane potential (TMP) was calculated using the Buswell equation (Symons and Buswell, 1933) and the substrate elemental composition. VS destruction was estimated by assuming the weight of VS destroyed was equal to that of the biogas produced. Total VFA concentrations are expressed in terms of chemical oxygen demand (COD) based on the theoretical COD of individual VFA species measured.

2.4 Modelling

Selected scenarios were modelled using ADAT, a mass and energy balance modelling tool developed with support from various sources including the FP6 CROPGEN project (SES6-CT-2004-502824), RCUK RELU (RES-229-25-0022), FP7 VALORGAS (241334), BBSRC ADNet (BB/L013835/1) and IEA Bioenergy Task 37 (UK), which is freely available for download from http://borrg.soton.ac.uk/resources/adat. The modelling tool calculates the energy requirement for heating of digester inputs, any pre or post-pasteurisation requirements (as specified by the user), and heat losses through the digester floor, walls and roof. It takes into account the efficiency of the CHP, includes estimated parasitic energy demands for mixing and pumping, and allows for fugitive methane losses in the process. It can also include energy requirements for transport and pre and post-processing of feedstock and digestate fractions, energy offset savings from fertiliser substitution and embodied energy in the major plant components, but these were not considered in the current work. The model is written in C# and compiled with a user interface allowing input values to be modified. Default values in the modelling tool were used unless otherwise noted.

3 Results

3.1 Stage 1: thermophilic co-digestion with SSD

Operating parameters: The applied OLR and HRT over the 235 days of operation during stage 1 are shown in Figure 1a and b. In general there were no disturbances to the planned operating conditions.

Gas production. Volumetric and specific biogas and methane production and biogas methane content during stage 1 are shown in Figure 1c-f. Volumetric biogas production (VBP) stabilised at around 0.56 L L^{-1} day^{-1} (Figure 1c), and gas composition remained steady at around 59% CH_4 (Figure 1d). Over the first 70 days where there was mono-digestion of OFMSW the specific methane production (SMP) appeared to stabilise at 0.307 m^3 CH_4 kg^{-1} VS. During the period of co-digestion with SSD from day 71 onwards the SMP fell to 0.203 m^3 CH_4 kg^{-1} VS (Figure 1e), while the total SMP based on the OFMSW input alone (Figure 1f) showed only a slight increase to 0.345 m^3 CH_4 kg^{-1} VS. This was mainly due to the low SMP of the SSD, although there may also have been some reduction in methane yield due to the shorter SRT and HRT.

Operational stability. pH in digesters T1 and T2 showed a small initial decline as the system acclimated to the change in feedstock followed by the increase in OLR (Figure 2a). By day 50 the pH had stabilised, however, and remained close to 8.0 for the rest of stage 1, despite the change in operating mode from day 71. TAN concentrations also remained relatively steady at around 2.3 g N kg^{-1} wet weight (WW) (Figure 2b). This is below the threshold for progressive VFA accumulation in thermophilic conditions, but close to the value where the first signs of mild instability may appear in the form of slightly elevated VFA concentrations (Yirong et al., 2017; Zhang et al., 2017a).

Total alkalinity (TA) in T1 and T2 dropped slightly with the initial change of feedstock, then fell more sharply as a result of the reduction in HRT from day 71 (Figure 2c). TA and partial alkalinity (PA) decreased to around 13.6 and 9.5 g $CaCO_3$ kg^{-1} WW respectively (Figure 2d and e): the reduction in intermediate alkalinity (IA) was proportionally less, with the result that the IA/PA ratio in both digesters rose from an initial value of around 0.3 to an average of around 0.4-0.5 (Figure 2f). The absence of any sudden changes in IA/PA ratio indicates, however, that these were still stable operating conditions for this feedstock (Ripley et al., 1986). Total solids content in T1 and T2 rose after the new feedstock was introduced, then fell from the introduction of solids wasting on day 71, and stabilised at around 6 %WW (Figure 2g). VS as a proportion of TS rose in the first 70 days (Figure 2h), reflecting the much lower biodegradability of the OFMSW feedstock compared to the source segregated food waste on which the digesters had previously been fed. By the end of stage 1 VS had stabilised at around 56% of TS, with an estimated overall VS destruction of ~42% based on biogas production.

Figure 2i and j show the total VFA concentrations in both digesters, and the individual VFA species in digester T2. In both T1 and T2 there was a brief peak in VFA associated with the initial change in feedstock, which reached around 6.5 g COD L^{-1} and consisted mainly of acetic acid. This fell rapidly and for the rest of stage 1 VFA in T1 remained below 1 g COD L^{-1}, though with continuing small fluctuations. VFA concentrations in T2 were slightly higher than in T1 and included 0.1-0.2 g L^{-1} of propionic acid. A one-off dose of TE solution was added to both digesters on day 80, but did not appear to have any immediate effect, and minor fluctuations in VFA continued. Total VFA in T2 started to fall from around day 175 and stabilised at below 1 g COD L^{-1} by the end of stage 1 (Figure 2j). This small difference between the digesters was also reflected in the TAN and TA concentrations and the IA/PA ratio, which were slightly higher in T2 than T1 for most of this period.

Average values for gas production and stability parameters over the last 20 days of stage 1, after 3.9 HRT and 7.8 SRT in the same operating mode, are shown in Table 2 below.

3.2 Stage 2: Thermophilic and mesophilic digestion without SSD addition

Operating parameters: Figure 3a and b show the OLR and HRT applied during stage 2. For the thermophilic digesters there were no disturbances to the planned conditions, apart from an accidental spill of around 3 kg of digestate from T1 on day 447. Over the next 8 days the daily OFMSW feed to T1 was reduced slightly in order to maintain an approximately constant OLR, and digestate removal was decreased until the digester reached its previous working volume, leading to a small temporary increase in HRT.

Feeding of the mesophilic digesters was adjusted in response to changes in the monitoring parameter values. Feeding of M1 followed the same pattern as in the thermophilic digesters until day 389, shortly after the start of the incremental rise in OLR. Feeding of M1 was stopped for 3 days, then an attempt was made to resume the OLR increase, but this was abandoned on day 398. M1 was left without feeding for 8 days, then the OLR was gradually stepped up between days 407-479 when it reached the previous value of 1 g VS L^{-1} day. M2 showed earlier and more severe signs of stress than M1, and reduced or intermittent feeding began on day 364 after 3 HRT under the new operating conditions. An attempt was made to increase the OLR in parallel with the other digesters between days 385-398, but this was abandoned and M2 was left without feeding for 11 days before the same stepped return to OLR 1 g VS L^{-1} day was applied as in M1. These changes in OLR were reflected in the HRT, which rose to infinity in the periods without feeding (Figure 3b).

Gas production. VBP, SMP and biogas methane content during stage 2 are shown in Figure 3c-e. In T1 and T2 following the switch from SSD to water addition the VBP fell, but stabilised after 5 days and reached an average of 0.490 L L^{-1} day^{-1} in the last 20 days before the OLR was increased from 1 to 2 g VS L^{-1} day^{-1}. VBP then increased in parallel with the rise in OLR between day 385-394. There was a small fall in VBP around day 450 for T1 and day 462 for T2: the reason for the former is unknown, while the latter was due to the reduction in feed associated with the digestate spill. Apart from day-to-day fluctuations VBP in T1 and T2 then remained stable, reaching an average of 0.999 L L^{-1} day^{-1} at the end of the experimental period. Gas composition in T1 and T2 remained steady at around 59% CH_4 (Figure 3d). SMP was closely similar in both digesters and averaged 0.290 L CH_4 g^{-1} VS in the last 20 days before the OLR increase, and 0.296 L CH_4 g^{-1} VS at the end of the run at OLR 2 g VS L^{-1} day^{-1}.

VBP in the mesophilic digesters at OLR 1 g VS L^{-1} day^{-1} was slightly lower than in the thermophilic (Figure 3c), with an average value of 0.452 L L^{-1} day^{-1} between day 343-362. From day 363 the OLR on M2 was reduced, with a corresponding fall in VBP, while M1 showed a slight downward trend in VBP despite the constant OLR. Subsequent variations in VBP reflected the applied loading rates, with VBP finally recovering to around its previous value once the OLR was restored to 1 g VS L^{-1} day^{-1}. Gas composition was relatively stable apart from a dip in CH_4 content around day 370 for M2 and a peak around day 407 in both M1 and M2 (Figure 3d). SMP averaged 0.267 L CH_4 g^{-1} VS for the two digesters between day 344-363 and 0.263 L CH_4 g^{-1} VS in the last 20 days of the run.

Operational stability. Figure 4 presents the values for monitoring parameters during stage 2. TAN concentrations in both sets of digesters initially fell as ammonia from the inoculum in M1 and M2 and from the SSD addition in T1 and T2 was progressively washed out (Figure 4a). After 3 HRT under the new operating conditions, TAN had stabilised and was slightly higher in the thermophilic digesters at an average of 0.42 g N kg^{-1} WW for day 365-384 than in M1 at 0.29 g N kg^{-1} WW. Feeding of M2 had altered after day 363 due to signs of instability, but until then it showed a closely similar trend to M1, while the slight increase in TAN in M2 after day 363 may indicate some associated biomass die-off and lysis.

TA and PA values mirrored the fall in TAN (Figure 4b-d), with the TA stabilising at around 3.8 and 3.6 and PA at 2.8 and 2.3 g $CaCO_3$ kg^{-1} WW in the thermophilic and mesophilic digesters respectively. After some minor fluctuations the IA/PA ratio settled at around 0.3-0.4 in all digesters (Figure 4e). The pH in both sets of digesters also gradually fell in response to the changing TAN, but from different start points and to different degrees (Figure 4f). In T1 and T2 the initial pH was just below 8.0, reflecting the higher initial TAN content of around 2.2 g N kg^{-1} WW. After 3 HRT, this appeared to be stabilising at pH 7.4. The initial pH in M1 and M2 was around 7.4 with a TAN content of 1.8 g N kg^{-1} WW and this stabilised at just above 7.0.

The main difference in digester operational stability parameters was in the VFA concentrations. T1 and T2 showed initial peaks in total VFA of up to 1.3 g COD L^{-1} immediately after the cessation of SSD addition. These declined to < 0.1 g COD L^{-1} by day 300 and remained very low throughout the rest of the trial, apart from a brief increase around day 363. These initial peaks were primarily acetic acid but also contained up to 0.5 g COD L^{-1} of propionic acid and small amounts of longer chain VFA. In contrast the mesophilic digesters had total VFA of < 0.1 g COD L^{-1} until day 363 when concentrations rose, especially in M2. It was thought this could be caused by washout of essential TE after 3 HRT; and as a precautionary measure on day 368 all four digesters were given a one-off dose of TE solution as described above. Total VFA concentrations in M2 fell to < 0.1 g COD L^{-1} by day 377 and values in the other digesters reduced even further. The attempt at raising the OLR in M1 and M2 led to another increase in VFA concentrations, however, reaching 1.5 g COD L^{-1} in M2 and consisting almost entirely of acetic acid. VFA concentrations finally stabilised at very low levels after day 475 once the OLR was returned to 1 g VS L^{-1} day^{-1}.

Although the trial continued for a further 3.8 HRT after the one-off TE dosing there were no further TE additions and no sign of reappearance of VFA.

TS in both sets of digesters fell from the start of stage 2 (Figure 4g), stabilising at around 2.1 % in T1 and T2 and 2.2 % in M1 and M2 after 3 HRT, with VS/TS ratios of 57.9 and 59.7% respectively. After the increase in OLR in T1 and T2 there was a clear rise in TS content but a decline in VS/TS ratio to around 52%. Estimated VS destructions based on gas production were around 60% for the thermophilic digesters and 53% for mesophilic.

Table 2 shows average values for gas production and operational stability parameters over the last 20 days before the OLR increase from 1 to 2 g VS L^{-1} day^{-1}, and before the end of the experimental period. These periods correspond to 3.5 HRT and 7.0 SRT and to 3.1 HRT and 6.2 SRT respectively in each operating mode.

3.3 Energy and performance considerations

Characteristics for Batch 1 of the feedstock shown in Table 3, with typical values for mechanically-sorted OFMSW from a 'medium complex' plant (Cecchi et al., 2003) and those previously reported for waste from the same source (Zhang et al., 2012). The TS and VS values given in Table 3 are the average from the experimental period, with a relative standard deviation of approximately 5% in each case.

Table 3 also shows the calculated TMP and theoretical and measured HHV values for the OFMSW feedstock based on elemental composition, with values from Zhang et al. (2012) for comparison. Measured and theoretical HHV show good agreement, providing support for the elemental analysis results. The biogas methane content of 60.0% predicted by the Buswell equation is close to the observed average value of around 59.3%. The SMP of 0.290 L CH_4 g^{-1} VS achieved in thermophilic operation at OLR 1 g VS L^{-1} day^{-1} represents conversion of 42% of the TMP and 38% of the measured HHV. Equivalent conversion values for the SMP of 0.256 L CH_4 g^{-1} VS in mesophilic conditions are 37% and 34%. The methane yield of the OFMSW on a wet weight basis was 86 and 77 m^3 CH_4 $tonne^{-1}$ in thermophilic and mesophilic conditions respectively.

Zhang et al. (2012) reported a lower TMP and HHV, a higher mesophilic SMP of 0.304 L CH_4 g^{-1} VS, and thus higher conversion rates of 55% TMP and 55% HHV for material from the same plant. There were no known changes in on-site processing between the two trials; but Zhang et al. (2012) included an additional in-house pre-processing step in which small pieces of plastic and glass were manually picked out before feeding to the digesters. In addition to natural variation between batches and over time, this may account for the lower VS content and VS/TS ratio in the current feedstock (Table 3). Removal of small fragments of plastic will lead to an apparent increase in biogas and methane yield on a VS basis, which may partially account for the slightly higher SMP. On the other hand removal of plastics will reduce the measured and theoretical TMP and HHV, and may account for the lower values of these parameters compared to the current feedstock. Removal of inert materials (glass and metal fragments) will also slightly increase the SMP on a TS basis; while removal of both inerts and plastics may increase or reduce the HHW on a TS basis depending on the relative proportions removed. It is likely that at least part of the difference in conversion is due to the additional pre-processing by Zhang et al. (2012). Specific methane production on a wet weight basis was 20% lower in the current study, suggesting that there may have been some reduction in feedstock VS content and biodegradability between the two trials, perhaps due to increasing popularity of source separated collections for domestic food waste. This is also supported by the differences in measured and predicted biogas methane content in each case. The SRT of 21 days used in the current study was shorter than the 30 days in Zhang et al. (2012), and this may also have accounted for some of the difference. Zhang et al. (2012) measured the BMP of the feedstock at inoculum-to-substrate (i/s) ratios of 2:1 and 4:1 on a VS basis. At i/s 2:1 the methane production at 21 days was only 73% of the value at 28 days and 69% of the final BMP value, but at 4:1 it was respectively 97% and 95%.

In the current trial the SMP in thermophilic conditions was higher than in mesophilic (0.290 and 0.256 L CH_4 g^{-1} VS respectively at OLR 1 g VS L^{-1} day^{-1}). It is often stated that thermophilic digestion can give higher gas production, especially for feedstocks with relatively high lignocellulosic content. In some cases this is simply an assertion without supporting data, while in others insufficient detail is given on how or whether gas volumes have been normalised to STP: measurement at 35 or 55 ^{o}C gives a 6% difference in gas volume. In some technical trials where appropriate datasets are provided, significant improvements have been demonstrated (Cecchi et al., 1991; Fernández-Rodríguez et al., 2013). In the current work there is reasonable confidence in the data, as the gas counters used were calibrated approximately weekly against the collected volume of gas at a measured room temperature and pressure. Moisture content can also account for 5-6% of gas volume at 35 ^{o}C and 15-16 % at 55 ^{o}C; but in the method used any associated errors should be small as the gas bags were allowed to equilibrate to room temperature before measurement. It is therefore likely that there was a real difference in SMP at the two temperatures: while the nature of the digested material makes it difficult to obtain very accurate and consistent VS concentrations, a small difference in the VS/TS ratios (Table 2) may also support this. To further reduce small day-to-day differences in gas volume measurement, such as those seen on days 322 and 331, direct correction of gas counter data by continuous logging of ambient temperature and pressure would be beneficial.

The SMP in thermophilic conditions at OLR 2 g VS L^{-1} day^{-1} was closely similar to that at 1 g VS L^{-1} day^{-1}, at 0.296 and 0.290 L CH_4 g^{-1} VS respectively, indicating that the thermophilic digesters operated well at the lower OLR despite the lower TAN and alkalinity (Table 2). In mesophilic conditions, however, there were signs of reduced stability at the lower OLR, with IA/PA ratios of around 1 by the end of the experimental period (Table 2), and the appearance of VFA during periods of moderate loading increase (Figure 4h). This was probably linked to the low TAN concentration and associated reduction in buffering capacity in the mesophilic digesters (Figure 4a). The low TAN may possibly indicate a slightly lower degree of hydrolysis in mesophilic conditions. TAN concentrations in the thermophilic digesters rose from 0.42 to 0.75 g N kg^{-1} WW when the OLR was raised from 1 to 2 g VS L^{-1} day^{-1}, with the resultant increases in pH, TA and IA/PA ratio all suggesting improved operational stability. Zhang et al. (2012) reported stable operation at a TAN concentration of 1.4 g N kg^{-1} WW with total VFA concentrations < 0.1 g L^{-1} and a pH of 7.5 in mesophilic conditions. The higher TAN concentration is due to the higher OLR of 2 g VS L^{-1} day^{-1} but also to recycling of digestate liquor only, unlike the current trial where a proportion of water was added to simulate the operation of a number of full-scale UK AD plants working on this type of feedstock. Where digester TAN concentrations are low in this mode of operation, for example due to a reduction in OLR, increasing the digestate recycle and reducing water input may offer a simple means of improving stability and performance.

At an OFMSW OLR of 1 g VS L^{-1} day^{-1}, the addition of SSD reduced the SMP but gave a higher VBP (Table 2). If it is assumed that the SMP of the OFMSW fraction at this OLR was constant with or without SSD, the estimated SMP of the SSD is around 0.078 L CH_4 g^{-1} VS. This is slightly higher than the value of 0.04-0.06 L CH_4 g^{-1} VS typically found for this digestate when used as inoculum in long-term mesophilic BMP tests (unpublished data, University of Southampton), indicating that some additional hydrolysis may be occurring at the higher temperature. Alternatively the increased buffering capacity and addition of inoculum and trace elements in the SSD may lead to a slight increase in the OFMSW SMP; in either case, the overall methane productivity of the system is increased. The proportion of SSD added was sufficient to maintain the TAN concentration just below that associated with the onset of instability in thermophilic conditions. SSD addition might also have been beneficial to stability in mesophilic digestion, especially at the lower OLR, but this was not tested in the current work.

3.4 Modelling

The scenarios considered were those tested in the laboratory trials, i.e. thermophilic operation at OLR 1 kg VS m^{-3} day^{-1} with and without SSD addition (TH1 and TH1+SSD), thermophilic operation at OLR 2 kg VS m^{-3} day^{-1} without SSD addition (TH2), and mesophilic operation at OLR 1 kg VS m^{-3} day^{-1} without SSD addition (ME1). User-defined feedstock properties were based on average properties for the OFMSW used (Table 3) and on steady state gas production and composition data in Table 2. Feedstock parasitic energy demand was taken as 40 and 10 kWh $tonne^{-1}$ for OFMSW and SSD respectively, based on the model's default values for mechanically-recovered biodegradable municipal waste and sewage sludge, respectively.

The working volume of the digester was set at 3439 m^3 to give an OLR of 2 kg VS m^{-3} day^{-1} for an assumed OFMSW input of 8500 tonnes WW $year^{-1}$. Digester construction was taken as a steel tank with 75 mm of high performance insulation (typical U-value 0.0245 W m^{-1} K^{-1}, giving a composite heat transfer coefficient of 0.35 W m^{-2} K^{-1}), with gas stored in a separate gas holder. Digestion temperatures were set at 55 ^{o}C for thermophilic operation and 37 ^{o}C for mesophilic, with ambient conditions based on Southampton, UK (annual average air and soil temperatures 10.6 ^{o}C). In thermophilic conditions no separate pasteurisation step was included, since compliance with the Animal By-product Regulations (EC 1069/2009) may be achieved by providing a guaranteed HRT, e.g. through intermittent feeding and discharge. In mesophilic conditions pre-pasteurisation of the OFMSW at 70 ^{o}C for one hour was specified; based on earlier work this was assumed not to affect the methane yield of the OFMSW (Banks and Zhang, 2010). It was assumed that the biogas produced was used on site in a CHP plant with an electrical conversion efficiency of 38% and heat recovery of 47% of input biogas energy. Fugitive emissions were set at 0.5%.

Table 4 shows the output from the modelling. Total biogas and methane production are determined by the experimental SMP values: as expected, total energy output followed the same sequence, being highest for TH2, TH1+SSD, TH1 then ME1. All scenarios show a positive energy balance, even when waste input is halved in this operating mode.

The heat demand of the AD process is the same for all three thermophilic scenarios, but considerably higher for the ME1 scenario, due to the requirement for pre-pasteurisation. The relative proportions of the raw biogas energy required for heating thus show a wide range, from 3.6% for TH2 to 13.7% for ME1. Very small differences in the AD plant parasitic electricity demand are due to the degree of solids breakdown in each scenario. The model calculates the VS destruction based on biogas production and adjusts the amount of digestate accordingly; since the energy demand for centrifugation is based on the tonnage of digestate, this leads to a small reduction in scenarios with higher biogas yield.

Reducing the OLR from 2 to 1 kg VS m^{-3} day^{-1} halves the required CHP generation capacity, but adding SSD recovers some of this. For larger AD plants with multiple digesters and CHP generators the simplest response to a major fall in feedstock tonnages is to close one or more units down: but where there is a single line this option may not be practicable. The experimental and modelling results both suggest that under thermophilic conditions the plant could still operate with a positive energy balance at a substantially reduced loading; although this may not be economically attractive, particularly if a proportion of the income stream is obtained from gate fees. The results show clearly that the worst option would be to drop the operating temperature of the digester as this would reduce the biogas yield, and make the plant more susceptible to pH fluctuations as a result of loss of buffering capacity and a tendency for VFA accumulation in response to load variations. The scenario of mesophilic co-digestion with SSD was not tested experimentally, but could provide a solution for instability resulting from the loss of buffering, although the additional biogas production in mesophilic conditions is likely to be lower. Addition of SSD in thermophilic conditions gives a 48% increase in electricity available for export and a 22% increase in heat compared to the equivalent output for water addition.

The results for the scenarios tested were as expected, confirming the accuracy of the modelling with respect to the growing knowledge base gained from operation of OFMSW digesters over a number of years. The model does, however, provide a flexible tool for testing different scenarios at scale and can be used both to provide baseline values for comparison with alternative process options; and to assess the potential for integration of AD with other emerging waste management options and technologies. An example where further process integration could be applied is in the use of waste heat in drying OFMSW as pyrolysis feedstock. The model cannot, however, predict some of the unforeseen outcomes of such integration: as noted by Yang et al. (2018) the pyrolysis of OFMSW at higher feedstock solids concentrations is associated with greater toxicity of the aqueous fraction when used as an AD feedstock.

One potential benefit of using co-digestates such as SSD is the increased nutrient content and fertiliser value of the resulting digestate. In countries such as the UK, where digestate from municipal solid waste (MSW) can still be applied to industrial crops, the enhanced nitrogen content from the addition of SSD could in theory be beneficial. This route, however, is very likely to be closed off in the near future due to growing environmental concerns over issues such as microplastics, endocrine disrupters and other priority pollutants; in many countries land application of this material is already specifically prohibited. Thermal processing of the digestate is therefore the most likely option for final disposal of residues from MSW digestion in future. Where SSD and residual OFMSW both contain heavy metals and other contaminants making them unsuitable for land application, the case for co-digestion is potentially attractive, as the increase in total energy output from the CHP plant can provide a heat source for pre-drying the centrifugate solids. This would reduce the energy input required for incineration or gasification of digestate from these mixed contaminated sources. The model allows inclusion of a value for post-processing energy per tonne of digestate, and this could be explored further using experimental data from dewatering; but this was not included in the current work.

4 Conclusions

Thermophilic CSTR digesters fed on mechanically-separated OFMSW at a moderate OLR of 2 kg VS m^{-3} day^{-1} and operated to simulate a full-scale plant with combined digestate recycling and water addition showed stable operation with a specific methane production of 0.296 m^3 CH_4 kg^{-1} VS, equivalent to 87 m^3 CH_4 per tonne of waste input. VS destruction was estimated at 82% based on the weight of biogas produced. Operating in the same mode but at a lower OLR of 1 kg VS m^{-3} day^{-1} and constant HRT had no adverse effect on performance, with specific methane production of 0.290 m^3 CH_4 kg^{-1} VS (86 m^3 CH_4 tonne^{-1} OFMSW). Under mesophilic conditions at OLR 1 kg VS m^{-3} day^{-1} with the same operating mode, however, the specific methane yield was lower at 0.256 m^3 CH_4 kg^{-1} VS (77 m^3 CH_4 tonne^{-1} OFMSW); and signs of reduced operational stability were seen especially when at incremental increases in OLR were attempted. This was probably due to the low TAN concentrations, which stabilised at around 0.2 g N kg^{-1} WW and led to limited digester buffering capacity. In practice if the OLR in such a plant is to be reduced steps should be taken to maintain TAN and buffering capacity, e.g. by reducing water addition and allowing an increase in HRT.

When the water was replaced by addition of municipal wastewater biosolids digestate (SSD) at OLR 1 kg VS m^{-3} day^{-1} in thermophilic conditions, volumetric biogas and methane yields increased by around 20%. This may have been due in part to the addition of supplementary inoculum and trace elements, but a more likely explanation is the further hydrolysis and degradation of the mesophilically-digested biosolids. Modelling indicated that addition of SSD in thermophilic conditions gave a 48% increase in electricity available for export (from 0.45 to 0.67 GJ tonne^{-1} OFMSW) and a 22% increase in heat (from 1.21 to 1.48 GJ tonne^{-1} OFMSW) compared to the equivalent output for water addition.

If transport and handling costs permit, addition of SSD may be an alternative to fresh water inputs, but it is important to maintain the digester TAN concentration below the threshold value of around 2.5 g N kg^{-1} WW of digestate to avoid the onset of inhibition and intermittent or progressive VFA accumulation.

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Data accessibility statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Table 1 Experimental conditions

		Days	OLR	HRT	SRT	Scenario
			kg VS m^{-3} day^{-1}	days	days	name
Thermophilic T1 & T2	day 0-15	16	Variable	variable	equal to HRT	-
	day 16-70	55	1.0 OFMSW	approx 297	equal to HRT	-
	day 71-235	165	1.0 OFMSW, 0.7 SSD	42	21	TH1+SSD
	day 236-384	149	1.0 OFMSW	42	21	TH1
	day 385-393	9	Increasing	Falling	21	-
	day 394-525	132	2.0 OFMSW	42	21	TH2
Mesophilic M1 & M2	day 244-384	141	1.0 OFMSW	42	21	ME1
	day 385-478	94	Variable - increasing	42	21	-
	day 479-525	47	1.0 OFMSW	42	21	-

Note: Stage 1 refers to days 0-235, Stage 2 to days 236-525. OLR is shown as value in kg VS m^{-3} day^{-1} followed by feedstock type: with two feedstock the total OLR is the sum of both values.

Table 2 Average steady-state values for digestion monitoring parameters

	Unit	TH1+SS [a, b]	TH1 [a, c]	TH2 [a, d]	ME1 [c, e]	ME1 [a, d, f]
Temp	°C	55	55	55	37	37
MSW	kg VS m^{-3} day^{-1}	1.0	1.0	2.0	1.0	1.0
SS dig	kg VS m^{-3} day^{-1}	0.7	0.0	0.0	0.0	0.0
VBP	L L^{-1} day^{-1}	0.583 ± 0.005	0.490 ± 0.003	0.999 ± 0.000	0.432	0.457 ± 0.007
CH4	% vol	59.3 ± 0.2	59.3 ± 0.3	59.3 ± 0.0	59.2	59.1 ± 0.1
SMP	L CH_4 g^{-1} VS	0.203 ± 0.002 [g]	0.290 ± 0.000	0.296 ± 0.000	0.256	0.263 ± 0.002
pH	-	7.98 ± 0.02	7.44 ± 0.01	7.57 ± 0.01	7.04	6.94 ± 0.00
TA	g $CaCO_3$ L^{-1}	13.9 ± 0.0	3.8 ± 0.0	8.2 ± 0.04	3.6	2.9 ± 0.2
PA	g $CaCO_3$ L^{-1}	9.6 ± 0.2	2.8 ± 0.0	5.1 ± 0.5	2.6	1.5 ± 0.0
IA	g $CaCO_3$ L^{-1}	4.3 ± 0.2	1.0 ± 0.0	3.0 ± 0.1	1.1	1.4 ± 0.2
IA/PA	-	2.8 ± 0.0	0.4 ± 0.0	0.4 ± 0.0	0.4	0.9 ± 0.1
TAN	g N kg^{-1} WW	2.27 ± 0.0	0.42 ± 0.0	0.75 ± 0.0	0.29	0.19 ± 0.0
VFA	mg COD L^{-1}	532 ± 82	20 ± 0.3	21 ± 0.8	92	22 ± 0.3
TS	%WW	5.8 ± 0.1	2.1 ± 0.1	4.3 ± 0.0	2.2	2.2 ± 0.0
VS	%WW	3.2 ± 0.1	1.2 ± 0.1	2.2 ± 0.0	1.3	1.3 ± 0.0
VS	%TS	55.8 ± 0.9	57.9 ± 0.7	52.4 ± 0.6	59.7	57.7 ± 1.9
VS destruction [g]	%VS	42%	60%	61%	53%	56%

[a] Values shown as ± are range of averages for 2 digesters; [b] average day 215-234, i.e. end stage 1; [c] average day 365-384, i.e. before OLR step; [d] average day 505-524, i.e. end stage 2; [e] values for M1 only; [f] not full steady state, < 3 HRT at OLR 1 g VS L^{-1} day^{-1}; [g] based on combined organic load; [h] based on gas production

Table 3 Physico-chemical characteristics and energy values for ms-OFMSW substrate

Parameter	**Units**	**This study**	**Zhang et al. (2012)** [a]	**Cecchi et al. (2003)** [b]
Characteristics				
Total solids (TS)	g TS kg^{-1} wet weight (WW)	536	528	~540
Volatile solids (VS)	g VS kg^{-1} WW	296	336	~270
	% TS	55.1	63.5	47
Total Kjeldahl Nitrogen (TKN)	g N kg^{-1} WW	7.3	7.3	~6
C	%TS	28.8 [c]	33.0	-
H	%TS	4.7 [c]	3.8	-
N	%TS	1.4 [c]	1.3	-
S	%TS	0.2 [c]	0.3	-
O	%TS	16.1 [c]	24.2	-
Measured HHV	MJ kg^{-1} TS	15.4 [c]	13.9	-
Energy values				
TMP [d]	L CH_4 g^{-1} VS	0.684	0.548	-
Calculated biogas composition [d]	%CH_4	60.0	56.6	-
HHV of CH_4 in TMP [d]	MJ kg^{-1} TS	15.7	13.9	-
Theoretical HHV [d]	MJ kg^{-1} TS	15.3	13.9	-
Measured HHV	MJ kg^{-1} TS	15.4	13.9	-
Thermo SMP	L CH_4 g^{-1} VS	0.290	-	-
	% TMP	42%	-	-
	% measured HHV	38%	-	-
	m^3 CH_4 tonne^{-1} WW	86	-	-
Meso SMP	L CH_4 g^{-1} VS	0.256	0.304	-
	% TMP	37%	55%	-
	% measured HHV	34%	55%	-
	m^3 CH_4 tonne^{-1} WW	77	102	-

[a] Zhang et al. (2012); [b] Cecchi et al. (2003); [c] analysed by Yang et al. (2018); [d] calculated from elemental composition

Table 4 Modelling results

	Unit	TH2	TH1	TH1+SSD	ME1
Temperature	oC	55	55	55	37
OFMSW input	tonnes year^{-1}	8500	4250	4250	4250
Water input	tonnes year^{-1}	21,415	25,665	0	25,665
SSD input	tonnes year^{-1}	0	0	25,665	0
Total digester Input	tonnes year^{-1}	29,915	29,915	29,915	29,915
OLR	kg m^{-3} day^{-1}	2.0	1.0	1.7	1.0
Methane produced	m^{3} year^{-1}	728,003	364,002	432,065	330,292
	m^{3} tonne^{-1} OFMSW	86	86	102	77
VS destroyed	tonnes year^{-1}	1,516	758	900	688
Digestate for disposal	tonnes year^{-1}	28,399	29,157	29,015	29,227
Required CHP electrical capacity	kW	330	165	196	150
Parasitic heat demand	GJ year^{-1}	949	949	949	1,629
Parasitic electricity demand	GJ year^{-1}	3,450	3,001	2,999	3,002
Electricity for export	GJ year^{-1}	6,410	1,929	2,852	1,471
Heat for export	GJ year^{-1}	11,246	5,148	6,288	3,904
Total energy for export	GJ year^{-1}	17,655	7,077	9,141	5,375
	GJ tonne^{-1} OFMSW	2.1	1.7	2.2	1.3

List of Abbreviations

AD	Anaerobic Digestion
CHP	Combined Heat and Power
COD	Chemical Oxygen Demand
CSTR	Continuous Stirred-Tank Reactor
HHV	Higher Heating Value
HRT	Hydraulic Retention Time
IA	Intermediate Alkalinity
MSW	Municipal Solid Waste
ms-OFMSW	Mechanically-Separated Organic Fraction of Municipal Solid Waste
OFMSW	Organic Fraction of Municipal Solid Waste
OLR	Organic Loading Rate
PA	Partial Alkalinity
SMP	Specific Methane Production
SRT	Solids Retention Time
SSD	Sewage Sludge Digestate
TA	Total Alkalinity
TAN	Total Ammoniacal Nitrogen
TE	Trace Elements
TKN	Total Kjeldahl Nitrogen
TMP	Theoretical Methane Potential
TS	Total Solids
VBP	Volumetric Biogas Porduction
VS	Volatile Solids
WW	Wet Weight

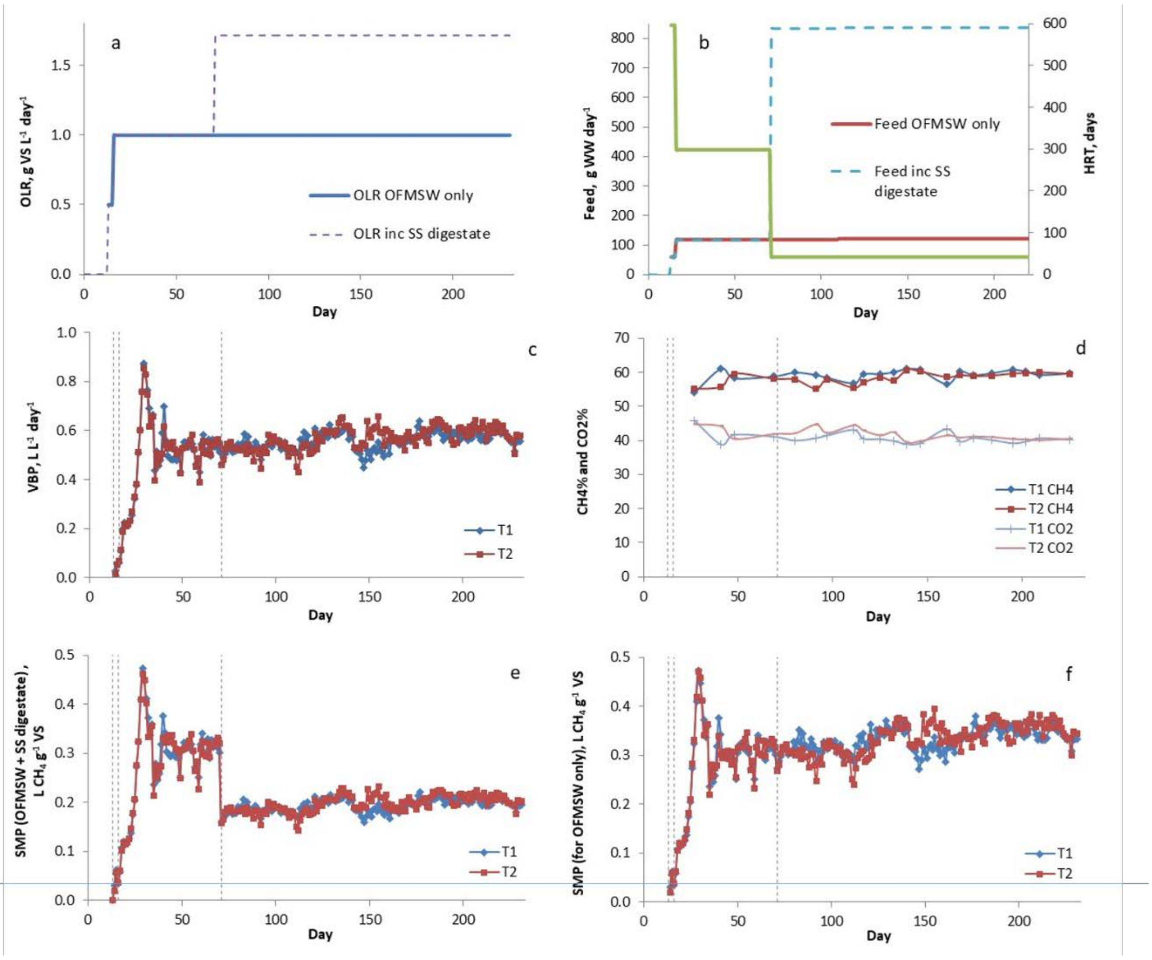

Figure 1. Organic loading rate (a), daily feed and hydraulic retention time (b), volumetric biogas production (c), biogas composition (d) and specific methane production based on OFMSW and SSD (e) and OFMSW only (f) for T1 and T2 during stage 1. Vertical dotted lines indicate change in OLR on days 13 and 16 and change in operating mode on day 69.

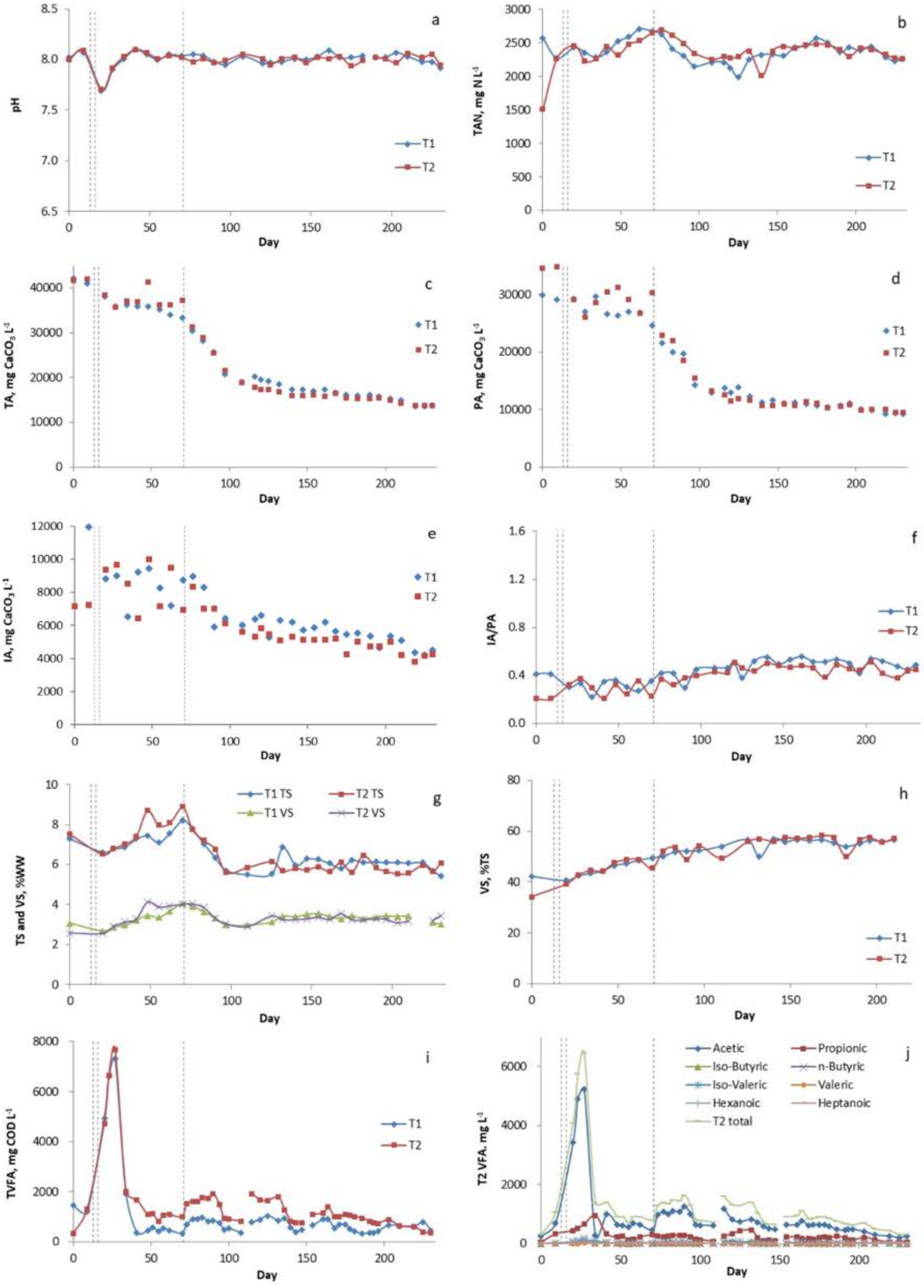

Figure 2. pH (a), TAN (b), TA (c), PA (d), IA, (e), IA/PA (f), TS and VS (g), VS as %TS (h), total VFA (i) and VFA profile (j) during stage 1. Vertical dotted lines indicate change in OLR on days 13 and 16 and change in operating mode on day 69.

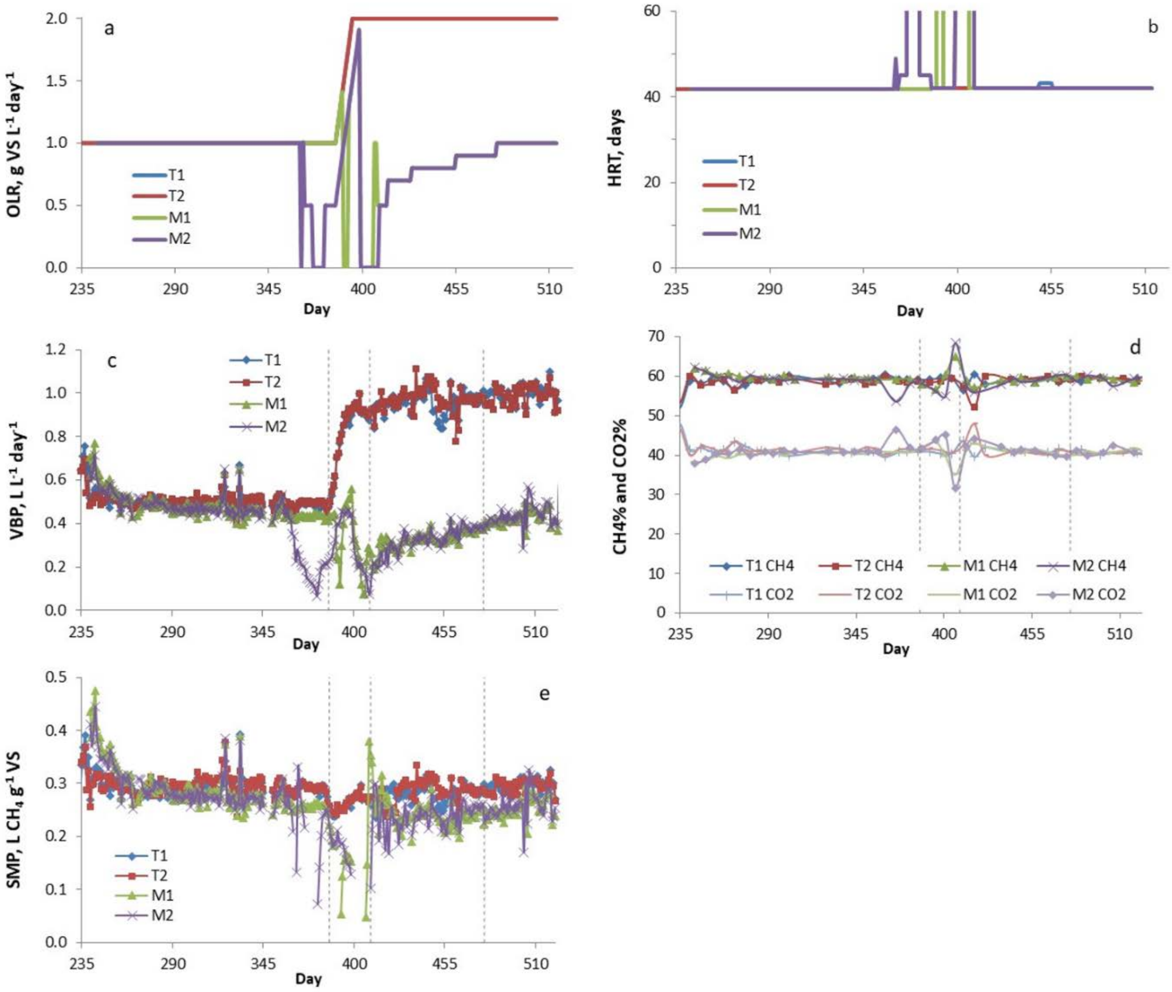

Figure 3. OLR (a), HRT (b) VBP (c), biogas composition (d) and SMP (e) in stage 2 for all digesters. Vertical dotted lines indicate changes in OLR as shown in Table 1.

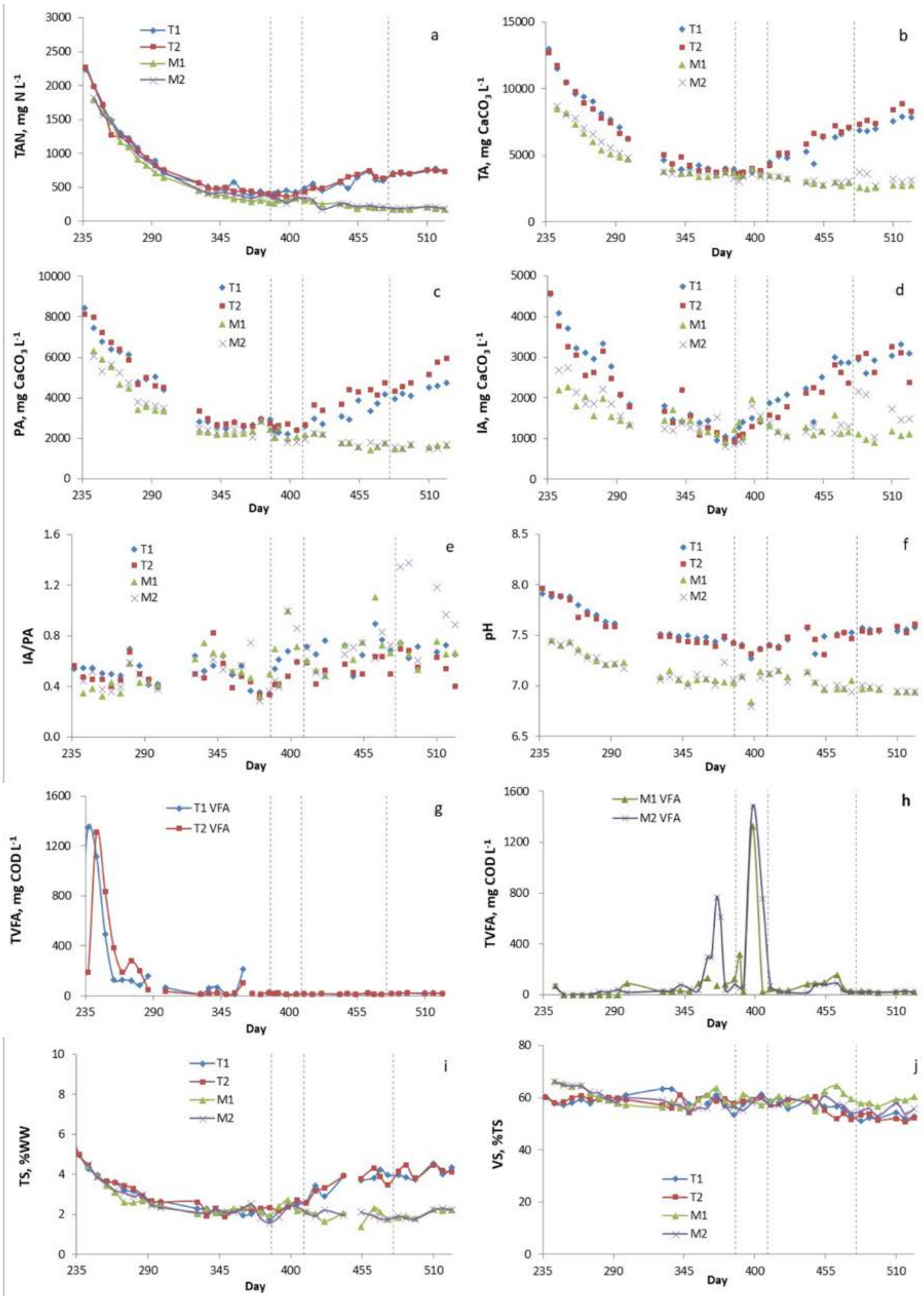

Figure 4. TAN (a), TA (b), PA (c), IA (d), IA/PA (e), pH (f), VFA (g and h), TS (i) and VS as %TS (j) for all digesters during stage 2. Vertical dotted lines indicate changes in OLR as shown in Table 1.