Banks, C.J., Chesshire, M. and Stringfellow A. (2008). A pilot-scale comparison of mesophilic and thermophilic digestion of source segregated domestic food waste. Water Science and Technology 58(7), 1475-1481. DOI 10.2166/wst.2008.513
http://www.iwaponline.com/wst/05807/wst058071475.htm

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# A pilot-scale comparison of mesophilic and thermophilic digestion of source segregated domestic food waste

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**ABSTRACT**
Source segregated food waste was collected from domestic properties and its composition determined together with the average weight produced per household, which was 2.91 kg per week. The waste was fed over a trial period lasting 58 weeks to an identical pair of 1.5 $m^3$ anaerobic digesters, one at a mesophilic (36.5 $^oC$) and the other at a thermophilic temperature (56 $^oC$). The digesters were monitored daily for gas production, solids destruction and regularly for digestate characteristics including alkalinity, pH, volatile fatty acid (VFA) and ammonia concentrations. Both digesters showed high VFA and ammonia concentrations but in the mesophilic digester the pH remained stable at around 7.4, buffered by a high alkalinity of 13,000 mg $l^{-1}$; whereas in the thermophilic digester VFA levels reached 45,000 mg $l^{-1}$ causing a drop in pH and digester instability. In the mesophilic digester volatile solids (VS) destruction and specific gas yield were favourable, with 67% of the organic solids being converted to biogas at a methane content of 58% giving a biogas yield of 0.63 $m^3$ $kg^{-1}$ VS $_{added.}$ Digestion under thermophilic conditions showed potentially better VS destruction at 70% VS and a biogas yield of 0.67 $m^3$ $kg^{-1}$ VS $_{added}$, but the shifts in alkalinity and the high VFA concentrations required a reduced loading to be applied. The maximum beneficial loading that could be achieved in the mesophilic digester was 4.0 kg VS $m^{-3}$ $d^{-1}$.

**Keywords:** Kitchen waste, mesophilic, thermophilic, volatile fatty acids, food waste

## INTRODUCTION

Alternative processing technologies for biodegradable municipal waste (BMW), such as anaerobic digestion, offer some potential for recovery of value from this material by producing soil-conditioning compost and biogas. There is rising interest in the technology in the UK due to the increasing energy costs associated with the processing of wet waste, the requirement to meet the targets of the landfill directive (EC, 1999), the regulations for the disposal of animal by-products (EC, 2005), and the rapidly increasing costs of landfill.

There are many examples of the use of anaerobic digestion (AD) for the treatment of BMW recovered from household waste as part of a mechanical-biological treatment process. Both ‘wet’ and ‘dry’ anaerobic technologies have been used for the biological stage (Mata-Alvarez, 2003). There are also examples of recovery of source segregated biodegradable wastes which are a mixture

of kitchen and garden wastes (Archer et al, 2005), but there are very few reports of AD plants operating entirely on the source segregated food waste fraction arising from domestic properties.

One of the possible reasons for this is that while food waste is an energy-rich substrate, there are some potential difficulties associated with its digestion which arise from its composition. The high protein content of food waste typically gives a high nitrogen content on hydrolysis, which leads to elevated concentrations of ammonia or ammonium ion in the digester. The distribution of the two species and their relative toxicity is pH dependent, with the more toxic form dominating at higher pH (Mata-Alvarez, 2003). High ammonia concentrations are also often associated with high volatile fatty acids (VFA) (Banks, 1994), although the ammonia provides alkalinity through the formation of ammonium carbonate, which helps to buffer the system allowing operation under these conditions (Gerardi 2003). There is still uncertainty as to the concentration at which ammonia becomes inhibitory and this is reflected in the various values given in the recent literature. According to Mata-Alvarez (2003), inhibition occurs at total ammonia concentrations of 1200 mg $l^{-1}$ and above. Hartmann and Ahring (2005) showed ammonia inhibition begins at free ammonia concentrations above 650 mg $l^{-1}$ $NH_3$-N, whereas Angelidaki *et al.* (2005) in a study of 18 full-scale biogas plants in Denmark co-digesting manure and organic waste only found decreases in efficiency when total ammonia was higher than 4000 mg $l^{-1}$ $NH_3$-N. It was recommended (Mtz-Viturtia, 1995) that wastes with C:N ratios lower than 10 should not be treated in one-phase systems at loading rates above 3 g COD $l^{-1}$ $d^{-1}$ due to instability caused by ammonia inhibition.

The aim of the research was to compare the mesophilic and thermophilic digestion of source segregated domestic food waste using two 1.5 $m^3$ pilot-scale anaerobic digesters operated in parallel in an identical manner in all respects other than temperature. In practice this was not entirely possible, as instability due to the build-up of VFA and a lowering of pH in the thermophilic digester required the loading to this digester be reduced part way through the trial

## MATERIALS AND METHODS

*Waste collection and preparation.* The research used source segregated food waste which was collected weekly from domestic properties in Burford Village, Shropshire, UK together with some catering wastes from a restaurant and cafe. The householders were provided with plastic bags in which the food waste was placed. These were weighed, split open and any contaminants removed before the contents were equally divided and blended with recycled digestate taken from the thermophilic and mesophilic digesters in separate storage tanks. Each mixture was further blended and kept mixed in the buffer storage tanks by recirculation through a macerator pump.

*Digestion plant.* The mesophilic and thermophilic digesters were identical in terms of size, shape and mechanical equipment as shown in Plate 1 and Figure 1. Each comprised a 1 $m^3$ buffer storage tank; a 1.5 $m^3$ closed digestion tank with gas recirculation mixing and an internal heater; a 1$m^3$ digestate storage tank; and a volume-calibrated bell over water gas collector. A 30-channel data logger (DT500, Datataker Ltd, Rowville, Australia) was used to record the output from thermocouples placed in the feed tank, the collection tank, and an array of 10 positioned in each digester at different levels within the vessel. Temperatures were logged at 10 minute intervals.

**Plate 1. Pilot scale digesters used in the study**

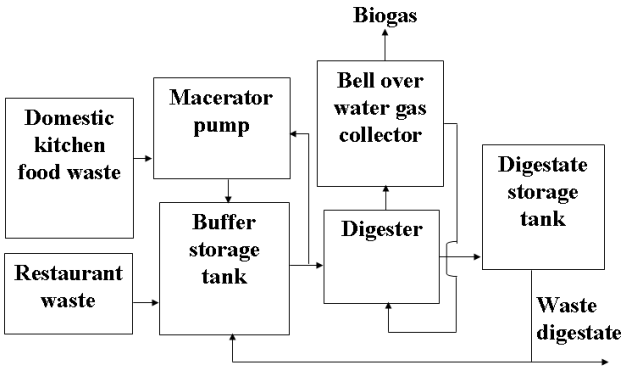



**Figure 1. Schematic flowsheet of the plant**

*Digester feeding regime.* The blended substrate was pumped batchwise 4 times a day into both the mesophilic and thermophilic digesters to guarantee a minimum residence time without bypass of six hours, and a nominal retention time of 28 days based on the food waste volume (assuming a density of 1.03 kg $l^{-1}$ when blended), at a design loading of 4 kg VS $m^{-3}$ $d^{-1}$. Before each feed a volume of digestate equal to that of the feed was pumped from each digester into its digestate storage tank. The feeding and monitoring period extended over 58 weeks to take into account of seasonal variations in the waste collected.

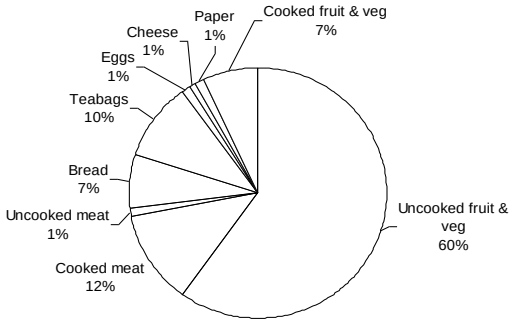
*Sampling and analysis.* The digestate and mixed feed were analysed for total solids (TS) and volatile solids (VS) using a gravimetric determination (APHA, 2005). Elemental composition of food waste and digestate was determined using an elemental analyser (FlashEA 1112, Thermo Finnigan, Italy) following the manufacturer's methods. VFA concentration and alkalinity were measured by titration of a 20 ml filtered sample to pH 4 with 0.1M HCl; the sample was then boiled for 3 minutes and back titrated with 0.01M NaOH to pH 4 and 7. The VFA acetic acid equivalent (mg $l^{-1}$) was calculated as the volume (ml) of sodium hydroxide titrated from pH 4 to pH 7 x 87.5. VFA concentrations were also measured using gas chromatography. The concentration of ammonia and other nutrients such as nitrate, phosphate and potassium were measured using a Dr. Lange test kits (Hach Lange Ltd, Manchester, UK). Methane concentration in the biogas was measured using a gas analyzer (Model GA2000,Geotechnical instruments, Leamington Spa, UK).

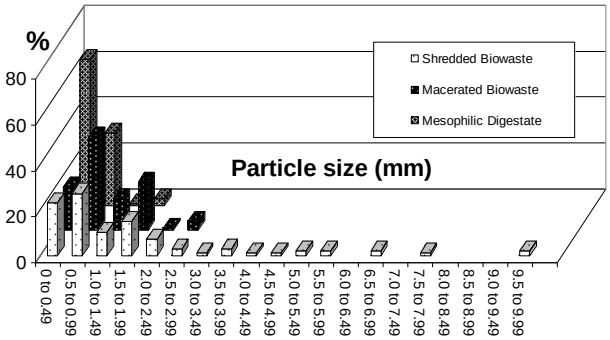
## RESULTS AND DISCUSSION

### Food waste collection and characteristics of the material

On average 2.94 kg food waste per household was collected every week. The average TS of the waste was 23% of which VS was 92%. The elemental composition of C, N, H, S, O was 55.52, 3.94, 8.53, 0.22, 29.1% respectively, accounting for 97.3% of the VS makeup and giving a carbon to nitrogen ratio of 14:1.

The average composition of the food waste was determined on two occasions from a sample of 10% of the weekly collected weight. Over 60% of the material was composed of uncooked fruit and vegetable waste; other major components were bread, tea bags, cooked meat and cooked vegetables. A particle size analysis was undertaken on 100 samples of the shredded food waste, blended mixed-feed and digestate and showed that most particles were less than 2 mm thick, and none were greater than 12 mm thick (Figure 2).




**a.** Proportion of food waste components

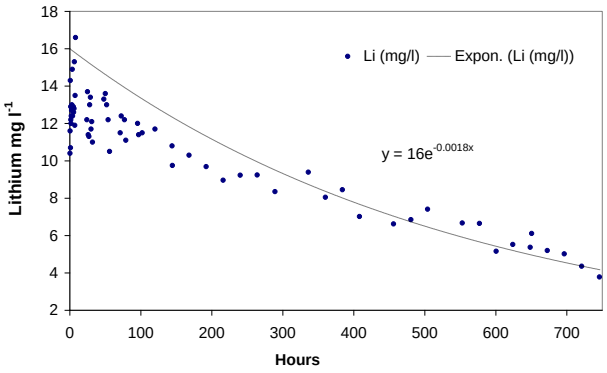
**b.** Frequency of particle size thickness (mm) of 100 samples of shredded raw food waste, mixed feed and digestate.

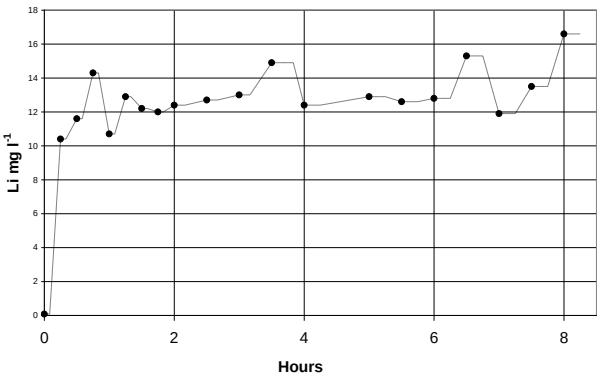
**Figure 2.** Food waste properties

The figure of 2.94 kg household$^{-1}$ week$^{-1}$ reflects UK Government statistics: the report 'Waste Not, Want Not' (2002) estimated food waste to be 17% of total household waste, equivalent to 3 kg household$^{-1}$ week$^{-1}$. These figures are also in agreement with a survey to estimate the total organic food waste generated by householders in Moray, Scotland, where an average of 2.91 kg of organic kitchen waste per week was measured (Jones, 2002). More recent studies on separate food waste collection in the UK (Hogg *et al*., 2007) have proposed values nearer to 4.0 kg household$^{-1}$ week$^{-1}$.

## Digester assurance testing

The average temperature of the thermophilic digester was 56.0$^{o}$C (+/- 0.21$^{o}$C); the average temperature for the mesophilic digester was 36.5$^{o}$C (+/- 0.28$^{o}$C). There were only slight variations between thermocouple readouts at different depths, showing that the mixing and heating systems were very effective at achieving a constant environment within the digester vessel. The mixing of the digesters was also confirmed using a lithium tracer test. The results from this are shown in Figure 3 which compares the experimental dilute-out curve with the theoretical model curve C= C0.e$^{-t/HRT}$ over a 750 hour period, and shows that uniform dispersion of the tracer in the reactor took place within 30 minutes.




a) Lithium tracer dilute curve

b) Dispersion of Lithium in the digester

**Figure 3.** Results of tracer studies

In both digesters biogas production varied throughout the year in response to operational changes. Both digesters had a tendency to develop high levels of VFA and ammonia in the digestate liquor,

and in the case of the thermophilic digester this had to be controlled by lowering the loading rate and increasing the retention time part way through the trial.

**Digestion trials**

*Mesophilic digester.* The mesophilic digester was started at a mean retention time of 31.5 days and a specific volatile solids loading rate of 4.1 kg VS $m^{-3}$ $d^{-1}$. The retention time was reduced over a number of weeks to 20 days (specific loading rate of 5.72 kg VS $m^{-3}$ $d^{-1}$) but this loading rate was found to be too high, causing accumulation of VFAs and pH depression.

The mesophilic digester produced on average 4.4 $m^3$ $d^{-1}$ of biogas comprising 59% methane. A biogas production of 140 $m^3$ per wet tonne of kitchen waste was achieved, a high value considering the total solids content of the material was only 23%; this was compensated for, however, by a VS destruction rate of 67% resulting in a digestate total solids of 5.5% with VS of 75%. There was an initial rise in digester VFA concentration reaching a maximum of 27,400 mg $l^{-1}$ after 35 weeks of operation. These high VFA levels did not appear to interfere greatly with gas production or solids destruction. The high ammonia concentration of around 5200 mg $l^{-1}$ added to the alkalinity of the system which, expressed as bicarbonate, averaged 13900 mg $l^{-1}$. This high alkalinity was sufficient to buffer the VFA resulting in a pH between 7.3 and 7.7. To reduce the level of VFA and ammonia some of the digestate recycle was replaced with water. This reduced the VFA concentration which then stabilised between 7000-12,000 mg $l^{-1}$ with a lower ammonia concentration of around 3000 mg $l^{-1}$ from week 39 onwards. Key parameters as weekly average values are shown in Figure 4.

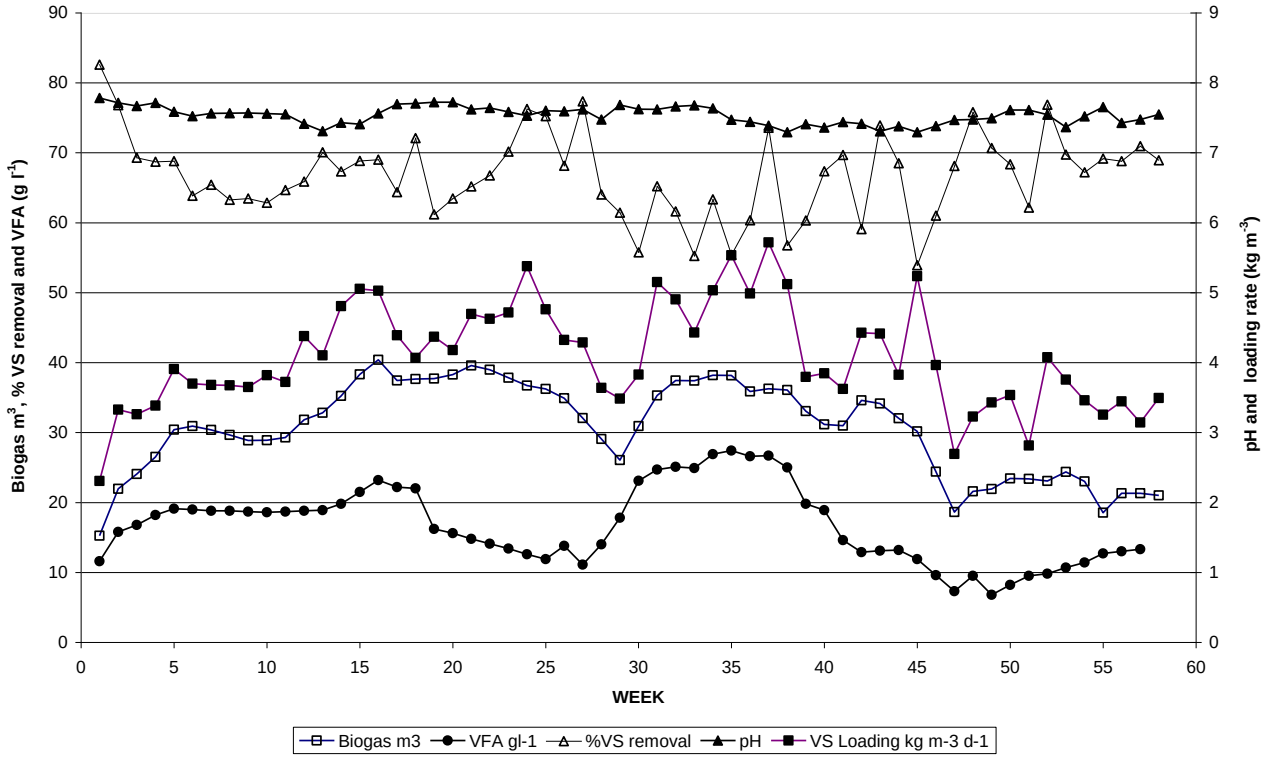



**Figure 4.** Key operational parameters from the mesophilic digester over the 58 week trial

*Thermophilic digester.* The mean hydraulic retention time was approximately 27 days over the first 25 weeks of the trial, and during the period of low loading this retention period was maintained by the addition of water to compensate for the reduced volume of food waste being added. The digester produced on average 3.1 $m^3$ $d^{-1}$ biogas and 58% methane. This overall lower efficiency of the digester over the trial period can be explained by the lower average load applied to the digester in

response to very high VFA concentrations accumulating in the digester mixed liquor, which reached a level of around 40,000 mg $l^{-1}$ by week 25. The feed to the digester was stopped in week 27 and then resumed at a lower loading of around 1 kg VS $m^{-3}$ $d^{-1}$ in week 29 and continued at this loading until week 39. During this time the biogas production dropped from around 30 $m^3$ $week^{-1}$ to between 5-10 $m^3$ $week^{-1}$ and the VFA concentration reduced to around 14,000 mg $l^{-1}$. The loading was then gradually increased again to 3.0 kg VS $m^{-3}$ $d^{-1}$ by week 47, and over the last 10 weeks of the trial averaged 3.6 kg VS $m^{-3}$ $d^{-1}$ with a weekly biogas production of 226 $m^3$. During this period there was again an increase in VFA to a final concentration of 28,000 mg $l^{-1}$ when the trial finished. This was despite part of the digestate recycle being replaced with water when feeding restarted in week 29. Taking into account this load reduction, the overall specific biogas yield for the thermophilic digester was 0.67 $m^3$ kg $VS_{added}$ $d^{-1}$ The digestate total solids averaged 5.4% with a VS content of 73.8%. The pH, alkalinity (16400 mg $l^{-1}$) and ammonia concentrations (5050 mg $l^{-1}$, reducing to 3600 mg $l^{-1}$ from week 29) were similar to those in the mesophilic digester except that the pH of the digestate dropped to 6.8 at one point when the VFA concentration reached 44,625 mg $l^{-1}$. Key parameters as weekly average values are shown in Figure 5.

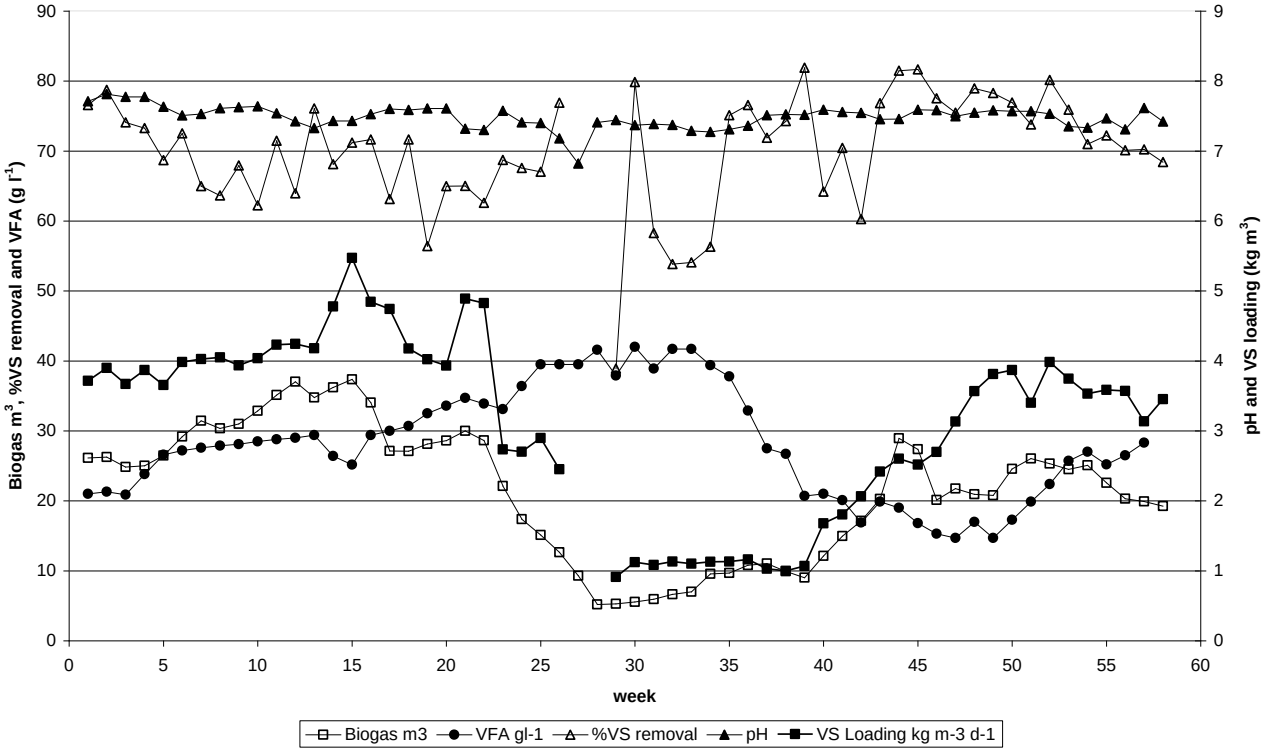



**Figure 5.** Key operational parameters from the mesophilic digester over the 58 week trial

*Performance indicators.* The pH in both the mesophilic and thermophilic digesters was relatively stable within narrow limits despite the large fluctuations in VFA concentrations, and proved to be a poor indicator of digester instability due to the delay in reaction time. This was due to the substantial buffering capability of the digestate. With the exception of one brief period in the thermophilic digester, the pH was within the limits of tolerance of methanogenic bacteria and good conversion was achieved. This indicates that, as long as the pH remained in this range, inhibition as a result of high VFA levels did not occur. This is similar to the self regulation seen in manure digesters where high free ammonia concentrations cause the accumulation of acetic and longer chain VFA as a result of acetogenic inhibition, but unless the magnitude of the accumulation is more than the system can withstand an equilibrium is attained where the VFA remain dissociated at the higher pH (Angelidaki, 1993).Both the mesophilic and thermophilic digesters had high alkalinity at 13,000 mg $l^{-1}$ (range 9,250 to 19,125 mg $l^{-1}$) and 16,400 mg $l^{-1}$ (range 9,625-27,000 mg

$l^{-1}$) respectively. These are much higher than usually described in anaerobic digesters (typically 2000-4000 mg $l^{-1}$), due to the high nitrogen content of the food waste and the resulting high levels of ammonia. Concentrations of total VFA as high as 45,000 mg $l^{-1}$ (range 14,131-44,625 mg $l^{-1}$) were recorded in the thermophilic digester; in comparison the maximum VFA concentration recorded in the mesophilic digester was 28,000 mg $l^{-1}$ (range 6,825-28,263 mg $l^{-1}$). The VFA concentration gave a rapid indication of the digester stability and acetic acid and propionic acids were the main VFA species that accumulated, with propionic acid seen mainly in the thermophilic digester but also in smaller concentrations under mesophilic conditions. Previous studies have indicated that VFA accumulation can been associated with a failure of the autotrophic methanogens which are able to use $CO_2$ and $H_2$ as precursors for methane production. Failure of this population can cause $H_2$ partial pressures to increase leading to high levels of propionic acid (Wiegant and Zeeman, 1986). This has been associated with ammonia nitrogen concentrations above 3500 mg $l^{-1}$ and also under these conditions an acetic acid product inhibition of butyric acid can be apparent (Ahring and Westermann, 1988). The carbon to nitrogen ratio of the digester feedstock (for both digesters) was 14:1 which is far lower than the 30:1 ratio often reported as optimal for digestion. During the digestion phase a substantial amount of the carbon is transformed into gaseous products leading to a reduction in the C:N ratio in the digestate to around 8:1 in the mesophilic digester.

One of the aims of the trial was to attempt to increase the loading rate to the digesters to 6 kg VS $m^{-3}$ $d^{-1}$ which has been achieved in other studies using BMW (Bolzonella, 2003). The mesophilic digester was started at a loading rate of around 3.5 kg VS $m^{-3}$ $d^{-1}$ which was gradually increased. Any increase above 4.0 tended to result in an increase in VFA and at loading above 4.5 kg VS $m^{-3}$ $d^{-1}$ was no additional biogas was produced. The loading pattern on the thermophilic digester was very similar increasing from around 3.7 to over 5.0 kg VS $m^{-3}$ $d^{-1}$; this rate was not sustainable however and feeding had to be suspended and the loading lowered as described above.

During the initial stages of the trial the thermophilic digester produced a higher biogas yield per kg of VS loaded with a maximum conversion rate of 1.1 $m^3$ $kg^{-1}$ $VS_{added}$ averaged over weeks 44 and 45 of the trial; some of this yield may have been due to further conversion of accumulated VFA. The average biogas yield was 0.67 $m^3$ $kg^{-1}$ $VS_{added}$ and the specific methane yield was 0.41 $m^3$ $kg^{-1}$ $VS_{added}$. This was higher than biogas and methane yields in the mesophilic digester, which were 0.63 and 0.39 $m^3$ $kg^{-1}$ $VS_{added}$ respectively. The maximum biogas yield of 0.8 $m^3$ $kg^{-1}$ $VS_{added}$ averaged over week 39 was also lower than in the thermophilic digester, but VFA levels were more stable in this digester. This suggests that if optimum conditions could be sustained, the thermophilic digestion process could produce a higher biogas yield than the mesophilic system. This is supported by the average VS reduction of the feedstock during the mesophilic digestion process which was 67% compared to a reduction of 70% in the thermophilic digester. There was no noticeable difference in the methane content of the biogas from the two digesters which averaged 58% in both. Trace gases were present at relatively low levels in the biogas with hydrogen sulphide at 1,300 to 1,700 ppm and slightly more carbon monoxide in the thermophilic biogas (290 to 700 ppm) compared to the mesophilic (200 to 500 ppm).

**Mass balance**

The results allowed a mass balance to be constructed for the operation of the mesophilic digester (Figure 6) which showed that a tonne of kitchen waste could be converted into 170 kg of biogas containing 60 kg of methane, and 830 kg of digestate for potential use as fertiliser or soil conditioner. The results have led to the design of a demonstration-scale plant which will receive 5000 tonnes per year of kitchen and garden organic wastes.

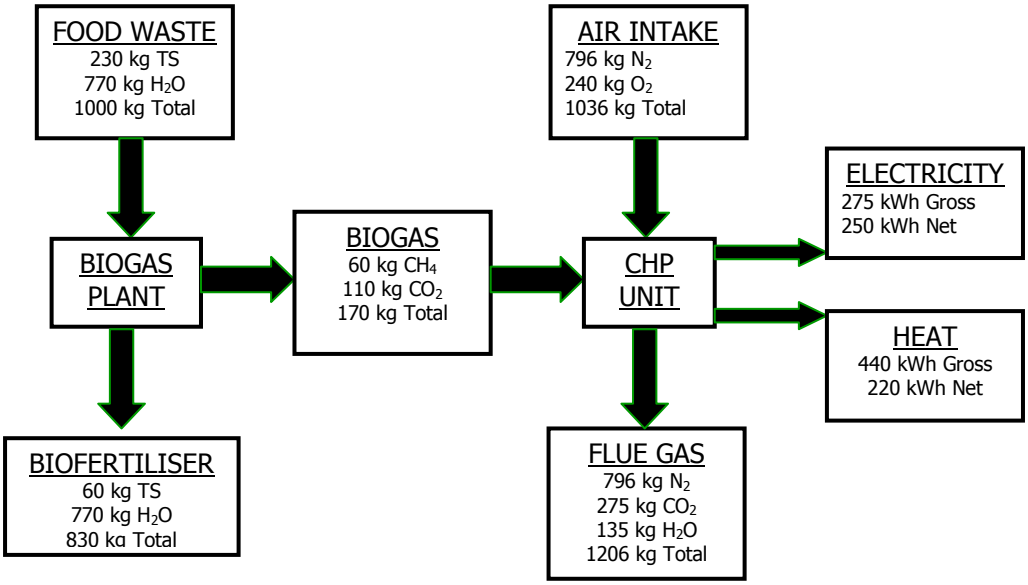



**Figure 6.** Mass balance around the mesophilic digester showing the energy gain and solid and liquid products from the digestion of 1000 kg of kitchen waste

## CONCLUSIONS

The digestion of source segregated food waste under mesophilic conditions proved to be reasonably stable over the 58 week trial period, despite the high concentrations of volatile fatty acids and ammonia present in the digester liquor. VS destruction and specific gas yield were favourable with 67% of the organic solids being converted to biogas with yield of 0.63 $m^3$ $kg^{-1}$ $VS_{added}$ at a methane concentration of 58%. Although digestion under thermophilic conditions showed a better solids destruction and biogas yield the process was unstable, with volatile fatty acids accumulating up to 45,000 mg $l^{-1}$ and causing the pH to drop to 6.8 with some loss of biogas production. In both cases the concentration of ammonia and VFA were reduced in the latter part of the trial by replacement of a part of the digestate recycle with fresh water.

## ACKNOWLEDGEMENTS

This project was funded under the UK Landfill Tax Credit Scheme by Biffaward. Thanks are also due to Lisa Pritchard of Greenfinch for carrying out much of the laboratory analytical work.

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