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SID 5 Research Project Final Report

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Project identification

1. Defra Project code: WR0212
2. Project title: Optimising inputs and outputs from anaerobic digestion processes
3. Contractor organisation(s): University of Southampton
4. Total Defra project costs (agreed fixed price): £ 213,590
5. Project: start date .... 01 January 2007
   end date .... 31 March 2009

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Executive Summary

7. The executive summary must not exceed 2 sides in total of A4 and should be understandable to the intelligent non-scientist. It should cover the main objectives, methods and findings of the research, together with any other significant events and options for new work.

Anaerobic digestion (AD) is an attractive waste treatment process in which both pollution control and energy recovery can be achieved. It involves the degradation and stabilisation of organic materials under anaerobic conditions by micro-organisms and leads to the formation of biogas (a mixture of carbon dioxide and methane) which is a renewable energy source, and a residual digestate that can be applied to land. A wide range of municipal, commercial, agricultural and industrial wastes have potential for anaerobic digestion because they contain high levels of biodegradable materials. Problems such as low methane yield and process instability are sometimes encountered in anaerobic digestion, however, restricting its use in certain circumstances.

The project aimed to provide a better understanding of some factors influencing the anaerobic stabilisation of biodegradable municipal waste (BMW). In particular the research addressed whether the process, as judged by volumetric biogas production, solids destruction and bio-stability of the residues, could be improved by co-digestion with other organic wastes from industry, commerce and agriculture. The research adopted a systematic approach based on an objective methodology to investigate the above factors. Two municipal waste streams (one source-segregated domestic food waste and one post-collection mechanically-recovered BMW) were selected as parallel substrates for a baseline study. These were blended with selected wastes arising from commercial, industrial and agricultural sectors. Both batch and semi-continuous anaerobic digesters were operated at laboratory and pilot scale. Their performance was monitored using a range of standard operating parameters and analytical measurements to assess the efficiency and long-term stability of the process. Suitable waste mixtures were suggested for stable and efficient anaerobic degradation, and optimal digestion conditions were identified based on the experimental results. Lastly, the digestate output was assessed for its biostability and potential value for land application.

Physico-chemical characterisation showed that source-segregated food waste had a high organic content and was rich in lipids and proteins, indicating the potential for a good biogas yield with a high methane content. These characteristics may also lead to inhibitory effects on the digestion process, however, as a result of the potential for volatile fatty acids formation and ammonia accumulation. The mechanically-recovered BMW had a lower organic matter content with a higher percentage of fibre, implying a lower biogas yield and methane content than food waste. The more favourable carbon to nitrogen (C:N) ratio of mechanically-recovered BMW should however lead to more stable digestion. The high nutrient content of food waste and its low concentration of potentially toxic elements (PTE) gave the digestate good properties as a fertiliser suitable for agricultural application. The mechanically-recovered BMW had higher concentrations of PTE and a lower nitrogen content, which may restrict its beneficial use.

Results from batch and semi-continuous experiments with mechanically-recovered BMW confirmed its operational stability: the organic loading rate (OLR) on the digesters based on volatile solids (VS) was successfully increased to 4 kg VS m^{-3} d^{-1} with a volumetric biogas production of 2.1 m^3 m^{-3} d^{-1} (corrected to standard temperature and pressure (STP)) and a methane content of 58%. The stability of operation was attributed to good buffering capacity, with a safe total ammonia nitrogen (TAN) concentration of 1.6 g l^{-1} and a pH of 7.4. It is possible that higher loadings could be achieved, as the TAN level will not rise above 3.0 g l^{-1} in a wet continuously stirred tank reactor (CSTR) process. It was not possible to determine an upper loading limit within the timescale of this project.

The digesters fed with food waste as a single substrate had a higher specific biogas yield and a higher percentage of VS removal compared with mechanically-recovered BMW in the early stages of continuous operation. As the duration of operation continued, however, there was a build-up of volatile fatty acids (VFA) and ammonia indicating long-term process instability. All laboratory-scale and larger-scale food waste digesters operated in the study showed similar patterns of accumulation.

Co-substrates were selected in the case of food waste to balance the C:N ratio, and for mechanically-recovered BMW to include readily-degradable high nitrogen content materials that would improve the overall biogas production and enhance the nutrient content of the digestate. The co-substrates for food waste were potato processing wastes, used office paper, card packaging, cattle slurry, and whey. Mechanically-recovered BMW was co-digested with blood and slaughterhouse waste (pig gut with flotation fat).

With respect to food waste digestion, the successful co-substrates capable of improving the performance were cattle slurry and card packaging. Addition of cattle slurry provides buffering capacity and essential elements, as well as a continuous inoculum of anaerobic microorganisms. Card packaging created a mixture with a similar nutrient composition to mechanically-recovered BMW, but without the gross physical contaminants (plastics, metal and glass) and PTE present in mechanically-recovered BMW. As well as lowering the overall nitrogen content of the feedstock mixture, card packaging also contributes some trace elements essential to the metabolic functioning of autotrophic methanogens. High nitrogen and high energy co-substrates produced less favourable conditions when used with mechanically-recovered BMW, and would be likely to restrict the overall loading, thereby negating any potential process advantages.

Pre-pasteurisation treatment did not show a significant effect on the rate of production or final biogas yield of the substrates tested. Whilst there is a requirement under the Animal By-products Regulations (ABPR) for pasteurisation of waste streams containing or contaminated by animal by-products to sanitise them and prevent pathogen transfer, the results of this work indicated that the option of pre-pasteurising waste streams before feeding them to the digester is unlikely significantly to affect the process efficiency of anaerobic digestion.

The research identified a requirement for addition of trace elements to digesters operating on food waste only. This is necessary to overcome deficiencies that will affect digestion performance by the inhibition of acetoclastic methanogenesis due to ammonia toxicity. It is proposed that further research is undertaken to develop methods of reducing the overall ammonia load in food waste digesters should be developed or that co-substrates should be used to balance the C:N ratio, provide essential elements and improve the overall efficiency of the digestion process.

Abbreviations

ABPR Animal By-Products Regulations
BMP Biochemical Methane Potential
BMW Biodegradable Municipal Waste
CHNSO Carbon, Hydrogen, Nitrogen, Sulphur and Oxygen
C:N Carbon to Nitrogen ratio
CSTR Completely Stirred Tank Reactor
CV Calorific Value
FW Food Waste
GC Gas Chromatograph
HAc Acetic acid
HEM n-Hexane Extractable Material
HPr Propionic acid
MBT Mechanical Biological Treatment
MSW Municipal Solid Waste
NPK Nitrogen, Phosphorus, and Potassium
PTE Potentially toxic element
RDF Refuse Derived Fuel
SBP Specific Biogas Production
SMP Specific Methane Production
SRT Solids retention time
STP Standard Temperature and Pressure
TAN Total Ammonia Nitrogen
TK Total Potassium
TKN Total Kjeldahl Nitrogen
TOC Total Organic Carbon
TP Total Phosphorus
TS Total Solids
VBP Volumetric Biogas Production
VFA Volatile Fatty Acid
VMP Volumetric Methane Production
VS Volatile Solids

Project Report to Defra

8. As a guide this report should be no longer than 20 sides of A4. This report is to provide Defra with details of the outputs of the research project for internal purposes; to meet the terms of the contract; and to allow Defra to publish details of the outputs to meet Environmental Information Regulation or Freedom of Information obligations. This short report to Defra does not preclude contractors from also seeking to publish a full, formal scientific report/paper in an appropriate scientific or other journal/publication. Indeed, Defra actively encourages such publications as part of the contract terms. The report to Defra should include:

- the scientific objectives as set out in the contract;
- the extent to which the objectives set out in the contract have been met;
- details of methods used and the results obtained, including statistical analysis (if appropriate);
- a discussion of the results and their reliability;
- the main implications of the findings;
- possible future work; and
- any action resulting from the research (e.g. IP, Knowledge Transfer).

1 Introduction

Anaerobic digestion (AD) is an attractive waste treatment process in which both pollution control and energy recovery can be achieved. It involves the degradation and stabilisation of organic materials under anaerobic conditions by micro-organisms and leads to the formation of biogas (a mixture of carbon dioxide and methane) which is a renewable energy source, and a residual digestate that can be applied to land. A wide range of municipal, commercial, agricultural and industrial wastes have potential for anaerobic digestion because they contain high levels of biodegradable materials.

Problems such as low methane yield and process instability are sometimes encountered in anaerobic digestion, however, restricting its use in certain circumstances.

1.1 Aim and objectives

The overall aim of this project was to better understand the factors influencing the stabilisation of biodegradable municipal waste (BMW) in the anaerobic digestion process. In particular the research addressed whether the process, as judged by volumetric biogas production, solids destruction and bio-stability of the residues, could be improved by co-digestion with other organic wastes from commerce, industry and agriculture. Two municipal waste streams (one from source-segregated material and one after post-collection recovery) were selected as parallel baseline materials for anaerobic treatability studies, against which waste blending from commercial, industrial and agricultural sectors was compared. The study involved determination of the physico-chemical characteristics of the wastes and the operation of anaerobic digestion trials in both batch and semi-continuous processes using them as feedstock. The digestion performance resulting from different wastes / waste mixtures was then used to identify the basic factors controlling the efficiency and long-term stability of the anaerobic digestion process. Suitable wastes and waste blends for stable and efficient anaerobic degradation were suggested and the optimal digestion conditions were chosen based on the experimental results. Lastly, the digestate, the output of the digestion process, was assessed for its biostability and potential value for land application.

The specific technical and scientific objectives were as follows:

1. Characterisation of two municipal waste streams used in a baseline study: one from source-segregated material and one after post-collection segregation.

2. Identification and selection of potential co-substrate feedstocks from the commercial, industrial and agricultural sectors.

3. Characterisation of identified co-substrates for digestion.

4. Determination of biochemical methane potential (BMP) from the two municipal solid waste (MSW) substrates both in isolation and combination with co-substrates from commercial, industrial and agricultural sources, including a pre-pasteurisation step for animal by-products regulations (ABPR) substrates.

5. Laboratory-scale trials using both types of MSW and co-substrates to determine process loading rates and reactor conditions for optimisation of biogas production.

6**.** Digestion trials at a larger scale to validate laboratory data and establish standard operating conditions.

7. Assessment of the characteristics of digestates (including separation of the solid and liquid fractions) from different mixtures of substrates for their potential value as agricultural products.

8. Measurement of the biostability of the solids-separated fraction of digestates from different mixtures of substrates in relation to landfill acceptance criteria.

2 Characterisation of MSW waste streams (objective 1)

2.1 Physico-chemical analysis

The two selected municipal waste streams were source-segregated food waste and post-collection mechanically-recovered biodegradable municipal waste (BMW), taken from two full-scale plants operated by Biocycle in Ludlow and Biffa Waste Services in Leicester. In both cases representative samples (>100 kg) were taken from the waste stream, homogenised and stored by freezing in sealed containers. Samples of the materials were characterised according to their physico-chemical properties on the basis of: those likely to influence the operation of the digestion process; those that can be used in prediction of the digestion performance and energy yield; and those of importance with respect to the potential for land application of residue (digestate). In addition, elemental analysis was conducted to allow comparison of the experimental results with theoretical predictions of biogas yield.

There were distinct differences in the physico-chemical characteristics of the two baseline waste streams. Source-segregated food waste had a much higher water content, a higher volatile solids content and a lower inert fraction compared to post-collection mechanically-recovered BMW on a total solids (TS) basis (Table 1). Food waste had a higher percentage of carbohydrates, lipids and proteins on a volatile solids (VS) basis, which indicates it is likely to have a higher calorific value, and the potential for greater biogas yield with a higher concentration of methane (CH_4). The absence of paper and card in food waste also gave it a lower fibre content. On the other hand, the relatively high lipid and protein content of the food waste can lead to inhibitory effects on the anaerobic digestion process. The higher fibre content of mechanically-recovered BMW implied it was likely to have less methane potential than food waste, although the higher carbon-to-nitrogen (C:N) ratio was closer to typical values where stable digester operation has been reported.

Table 1 Characteristics of the baseline waste streams

	Food waste	Mechanically-recovered BMW
General		
pH (1:5)	4.71 ± 0.01	6.39 ± 0.01
TS (% wet weight (WW))	23.74 ± 0.08	52.83 ± 0.63
VS (% WW)	21.71 ± 0.09	33.55 ± 0.63
VS (% of TS)	91.44 ± 0.39	63.52 ± 1.89
Total Organic Carbon (TOC) (% of TS)	47.6 ± 0.5	34.8 ± 1.1
Total Kjeldahl Nitrogen (TKN) (% of TS)	3.42 ± 0.04	1.39 ± 0.08
TOC / TKN	13.9 ± 0.2	25.0 ± 1.6
Biodegradable C / TKN	13.6 ± 0.2	19.1 ± 1.6
Calorific value (CV) (kJ g^{-1} TS)	20.7 ± 0.2	13.9 ± 0.2
Biochemical composition (VS basis)		
Carbohydrates[a] (g kg^{-1})	453 ± 17	340 ± 7
Lipids[b] (g kg^{-1})	151 ± 1	68.6 ± 5.4
Crude proteins (g kg^{-1})	235 ± 3	130 ± 7
Hemi-cellulose (g kg^{-1})	38.1 ± 3.7	52.2 ± 12.4
Cellulose (g kg^{-1})	50.4 ± 1.6	252 ± 36
Lignin (g kg^{-1})	16.5 ± 0.2	184 ± 26
Nutrients and PTE (TS basis)		
TKN (g kg^{-1})	34.2 ± 0.4	13.9 ± 0.8
Total Phosphorus (TP) (g kg^{-1})	5.41 ± 0.32	2.17 ± 0.25
Total Potassium (TK) (g kg^{-1})	14.3 ± 0.8	4.26 ± 0.37
Cd (mg kg^{-1})	< 1.0	1.50 ± 0.37
Cr (mg kg^{-1})	29.0 ± 1.2	263 ± 11
Cu (mg kg^{-1})	7.20 ± 0.81	107 ± 10
Hg (mg kg^{-1})	< 0.010	0.179 ± 0.018
Ni (mg kg^{-1})	7.0 ± 2.9	97.0 ± 2.9
Pb (mg kg^{-1})	< 10	162 ± 10
Zn (mg kg^{-1})	33 ± 11	259 ± 4

a: in equivalent glucose
b: n-hexane extractable material (HEM).

2.2 Digestion characteristics of the baseline waste streams (objective 4)

Both batch and semi-continuous digestion trials were conducted for the baseline waste streams. The batch trials, also referred to as biochemical methane potential (BMP) tests, are described in section 4 of the Technical Report, and the semi-continuous trials in section 5. Plate 1 shows the 1.4-litre and 75-litre digesters used in the research.

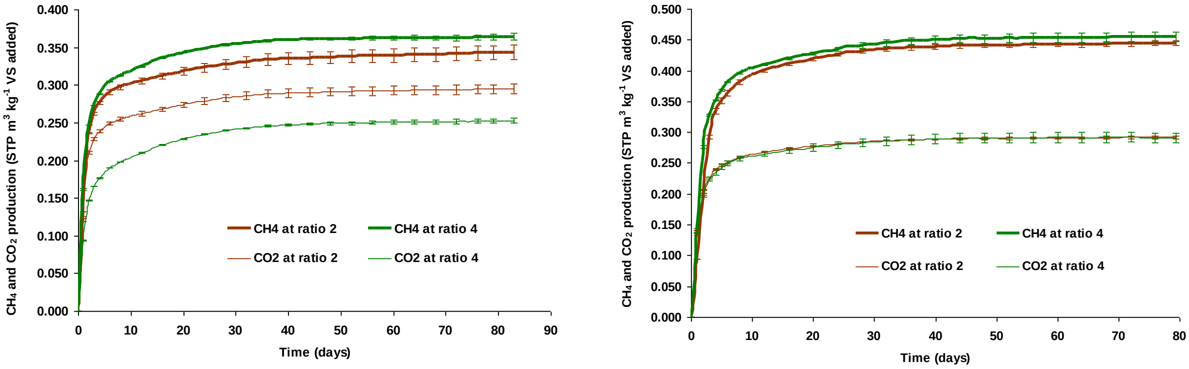
a) 1.4-litre BMP digesters

b) 75-litre digesters

Plate 1. BMP and larger-scale 75-litre digesters used in the study

2.2.1 Mechanically-recovered BMW

Mechanically-recovered BMW was a stable digestion substrate with a good biogas yield under the operational regimes utilised in the study. The BMP test on mechanically-recovered BMW ran for 82 days (Figure 1a). The percentage of methane at the most favourable of the two inoculum-to-substrate ratios used was 59% and the final BMP value was 0.364 m^3 CH_4 kg^{-1} VS_{added} at standard temperature and pressure (STP) of 0 ^oC and 101.325 kPa; this value was confirmed by a carbon mass balance which accounted for 96% of the carbon in the biogas and remaining in the digestate. The measured BMP was 91% and 65% of theoretical BMP values calculated based on the biochemical composition and Buswell equations respectively, indicating that a proportion of the substrate is recalcitrant to anaerobic biodegradation in the timeframe of the test. A second BMP carried out on both pasteurised and un-pasteurised material gave BMP values of 0.330 and 0.349 STP m^3 CH_4 kg^{-1} VS_{added} respectively, indicating that pasteurisation had no significant effect and confirming the earlier result for the un-pasteurised material (see section 4).



a) Mechanically-recovered BMW

b) Source-segregated food waste

Figure 1. BMP assay for baseline waste streams at inoculum-to-substrate ratios of 2 and 4

In semi-continuous digestion trials at a 35-litre scale the mechanically-recovered BMW was shown to be a suitable substrate in terms of stability. Both digesters used in this part of the study were able to acclimate to the substrate while running at a loading of 2 kg VS m^{-3} d^{-1} over 4 retention times, before digestate was removed as an inoculum for other experiments. Once the digesters had returned to their original volume, biogas production and specific biogas and methane yields recovered their former values (Figure 2a), with a slight increase in the biogas methane content. During this period the operational performance indicators were: specific methane production (SMP) 0.304 STP m^3 CH_4 kg^{-1} VS_{added}; specific biogas production (SBP) 0.529 STP m^3 kg^{-1} VS_{added}; volumetric biogas production

(VBP) 1.05 STP m^3 m^{-3} d^{-1}; methane percentage 57.5%; volatile fatty acids (VFA) concentration less than 100 mg l^{-1}; ammonia 1400 mg l^{-1} and a pH 7.5. The SMP accounted for 86% of the BMP value. The data indicated that most of the biodegradable part of mechanically-recovered BMW had been converted to biogas.

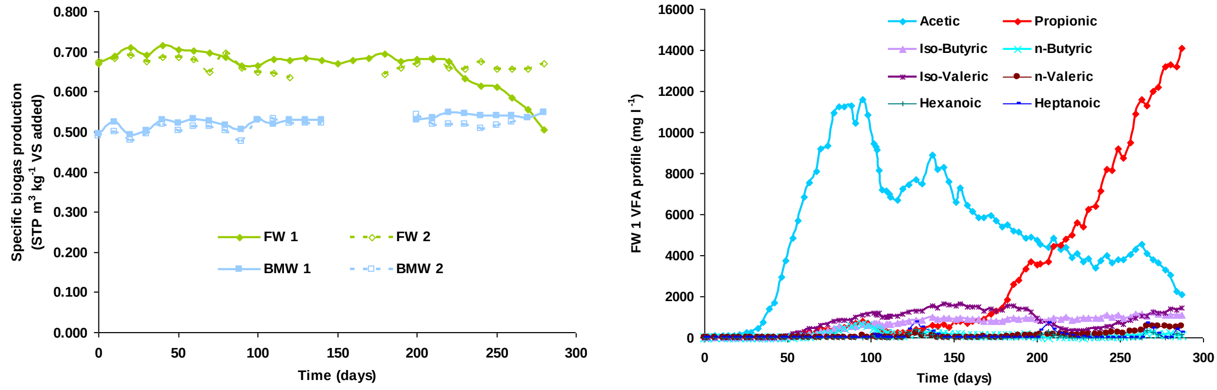
As part of the 4-litre laboratory-scale co-digestion trials one digester ran on mechanically-recovered BMW for a period of 425 days during which the organic loading rate (OLR) was increased from 2 kg VS m^{-3} d^{-1} (days 0-190) to 3 kg VS m^{-3} d^{-1} (days 191-350) and then to 4 kg VS m^{-3} d^{-1} (days 351-425). Throughout this period a solids retention time of 30 days was maintained by liquor recycling and solids wasting. The specific and volumetric methane productions are shown in Figure 4a and b. At the two lower OLR of 2 and 3 kg VS m^{-3} d^{-1} the SBP of ~0.52 STP m^3 kg^{-1} VS_{added} was similar to that observed in the 35-litre trial. The VBP of ~1.0 STP m^3 m^{-3} d^{-1} increased by 50% when the loading was increased to 3 kg VS m^{-3} d^{-1}. On increasing the OLR to 4 kg VS m^{-3} d^{-1} there was an initial drop in SBP, a rapid VFA accumulation (Figure 4d), a fall in pH and a lower methane concentration in the biogas. During the second retention time at this loading the specific biogas production recovered to its former level and the VBP increased to 2.1 STP m^3 m^{-3} d^{-1}, twice that achieved at an OLR of 2 kg VS m^{-3} d^{-1}. At this loading the VFA concentration stabilised at less than 150 mg l^{-1}, total ammonia nitrogen (TAN) at 1600 mg l^{-1} (Figure 4c) and pH at 7.4.

It is possible that higher loadings could be applied but this was not attempted. It should be noted, however, as the loading is increased the rheological properties of the digestate change as a result of the higher total solids (TS) content of the digester liquor. The digester TS at the highest loading was 170 kg m^{-3} which was close to the limit of the mechanical mixing system of the small-scale digesters used in this study.

2.2.2 Source-segregated foodwaste

Two sets of BMP tests were carried out on source-segregated food waste, the first of which ran for 80 days (Figure 1b). The biogas methane content at the most favourable inoculum-to-substrate ratio of 4 was 61% and the final BMP value was 0.456 STP m^3 CH_4 kg^{-1} VS_{added}. This value was confirmed by a carbon mass balance which accounted for 98% of the carbon in the biogas and remaining in the digestate. The measured BMP was 92% and 83% of the theoretical BMP values calculated from the biochemical composition and Buswell equations respectively, indicating that only a small proportion of the substrate is recalcitrant to anaerobic biodegradation in the timeframe of the test. A second BMP carried out on both pasteurised and un-pasteurised material gave values of 0.473 and 0.475 STP m^3 CH_4 kg^{-1} VS_{added} respectively, indicating that there was no significant effect from pasteurisation and confirming the earlier result for un-pasteurised material (see section 4).

In the semi-continuous digestion trials at a 35-litre scale one of the food waste digesters ran continuously with daily feeding for 9.5 retention times (284 days). The digester showed some initial disturbance when food waste was first added but then stabilised allowing performance indicator parameters to be determined for pseudo-steady state conditions during days 150-180. The SBP was 0.695 STP m^3 kg^{-1} VS_{added} (Figure 2a), VBP 1.39 STP m^3 m^{-3} d^{-1}; VFA concentration between 9000-10000 mg l^{-1}; ammonia 3800 mg l^{-1}, pH 7.7, and VS destruction 83.9%. The data indicated that most of the biodegradable part of the food waste had been converted to biogas, but with a large VFA pool remaining. From day 180 onwards, rises in propionic acid concentration (Figure 2b), a reduction in SMP, and the development of severe foaming problems indicated the digester was failing. A second 35-litre digester showed a similar trend but with a delay in the onset of propionic acid accumulation. The use of the digestate from the 35-litre trial as an inoculum for co-digestion work showed that recovery could be achieved, but continued feeding with food waste alone resulted in the further accumulation of propionic and, to a lesser extent, butyric acids.



a) Weekly average specific biogas production in food waste and mechanically-recovered BMW digesters

b) VFA concentration profile in Food waste digester 1 where specific biogas production fell from day 220

Figure 2. Results of baseline waste digestion trial in 35-litre digesters

A 75-litre digester was also run on food waste for 308 days as part of the larger digester trial at an OLR of 2 kg VS m^{-3} d^{-1} and a solids retention time of 30 days, starting from an inoculum of municipal sewage sludge digestate. As with the 35-litre digester there were initial disturbances during the first 60 days of operation as a result of the change of substrate from sewage sludge to food waste (Figure 6b and d). After a further 4 retention times (120 days) of steady state, operation VFAs started to accumulate from the previously stable concentration of around 200 mg l^{-1} and had reached 4000 mg l^{-1} by day 270. Initially the VFA was predominantly in the form of acetic acid (HAc) but later all the VFA species were present with an initial rise in propionic acid (HPr) concentration. During periods of pseudo-steady state operation the performance parameters were: SBP 0.705 STP m^3 kg^{-1} VS$_{added}$, SMP 0.425 STP m^3 kg^{-1} VS$_{added}$, VBP 1.42 STP m^3 m^{-3} d^{-1}, volumetric methane production (VMP) 0.855 STP m^3 CH$_4$ m^{-3} d^{-1}, 86.5% VS converted to biogas, 60.6% methane percentage in biogas, pH rising to 8.1, TAN rising to 4900 mg l^{-1}, free ammonia rising to 600 mg l^{-1}. The accumulation of VFA, and in particular the persistence of propionic acid, had been a feature of all of the semi-continuous food waste digestion trials. A full discussion of this is present in the main Technical Report, but, in summary, it is likely that at the high TAN concentrations found in the digestate the acetoclastic methanogenic population is severely inhibited. This causes a fundamental shift in the predominant biochemical route by which methane is formed, to autotrophic metabolism from hydrogen and carbon dioxide rather than directly from acetic acid. This shift requires different enzyme systems, some of which are dependent on essential trace elements that are deficient in food waste. Once the initial supply of these elements is diluted out of the system propionic acid will accumulate, probably as a result of the inability of the formate dehydrogenase enzyme to function.

3 Selection and characterisation of co-substrate wastes (objectives 2 and 3)

Only commercial, industrial and agricultural waste materials that are available in large tonnage quantities and distributed geographically throughout the UK were considered as potential co-substrates. From an initial scoping study fifteen wastes were shortlisted as co-substrates (cattle slurry, rumen content, office paper, paper pulp, brewery spent grain, waste yeast, whey, potato waste, and flourmill waste, card packaging, biodiesel by-product, blood, pig gut, slaughterhouse recovered fat, and poultry litter). These were collected from industrial and agricultural sources and characterised with respect to their biochemical composition, elemental composition, nutrient content, and concentration of potentially toxic elements (Table 2).

In summary, office paper, card packaging, paper pulp, potato waste and flourmill waste all had a high carbon to nitrogen (C:N) ratio making them candidates for co-digestion with source-segregated food waste. Of these, potato waste, flourmill waste and office paper had a lower lignin content than paper pulp or card packaging indicating their higher potential biodegradability and biogas production. Cattle slurry, sheep rumen content, spent grain, waste yeast, and whey all had a similar or lower C:N ratios compared to food waste making them less attractive as co-substrates. Although cattle slurry had a lower C:N ratio than the food waste and a low methane potential, it was still considered an attractive co-substrate because the addition of food waste, with its higher energy potential, could optimise the volumetric biogas productivity of a cattle slurry digester. As the tonnage of cattle slurry available nationally is much larger than the amount of food waste, it was decided that the relative proportion of food waste in a co-digestion mix should give a more realistic reflection of this ratio. On the basis of the experimental findings and taking into account the potential co-substrate characteristics, availability and tonnage quantities, it was decided to use cattle slurry, card packaging and potato waste as co-substrates in the laboratory-scale semi-continuous co-digestion trials with source-segregated food waste.

Sheep blood, pig gut, flotation fat, and poultry litter all had a high Total Kjeldahl Nitrogen (TKN) content and/or a high lipid content making these materials difficult to digest alone, but they also all have a high methane potential. Co-digestion of these with mechanically-recovered BMW would raise the specific methane production (SMP) of the input waste by lowering the fibre content and increasing the protein and lipids. The by-product from bio-diesel production (glycerol) also had a very high pH, no detectable nitrogen or fibre content and a low ash content, potentially making it a co-substrate for either of the base waste streams. On the basis of further experimental findings, availability and tonnage quantities, of the potential co-substrates it was decided that sheep blood and a mixture of pig gut and flotation fat would be used as co-substrates in the laboratory-scale semi-continuous co-digestion trials with residual mechanically-recovered BMW.

4 Effect of pasteurisation on anaerobic biodegradability (objective 4)

Where wastes contain or have been contaminated by meat or meat products, processing has to comply with the animal by-products regulations (ABPR). For digestion this is a relatively straightforward requirement as the process generates sufficient energy to allow a pasteurisation step in which the material, with a particle size of less than 12 mm, is held at 70 ^{o}C for 1 hour (EU ABP Regulation 1774/2002). The aim of this part of the research was to test the BMP of pasteurised wastes to assess whether pasteurisation / co-pasteurisation affected the kinetic and thermodynamic aspects of anaerobic degradation

Table 2 Characteristics of co-substrates (range values given in main Technical Report)

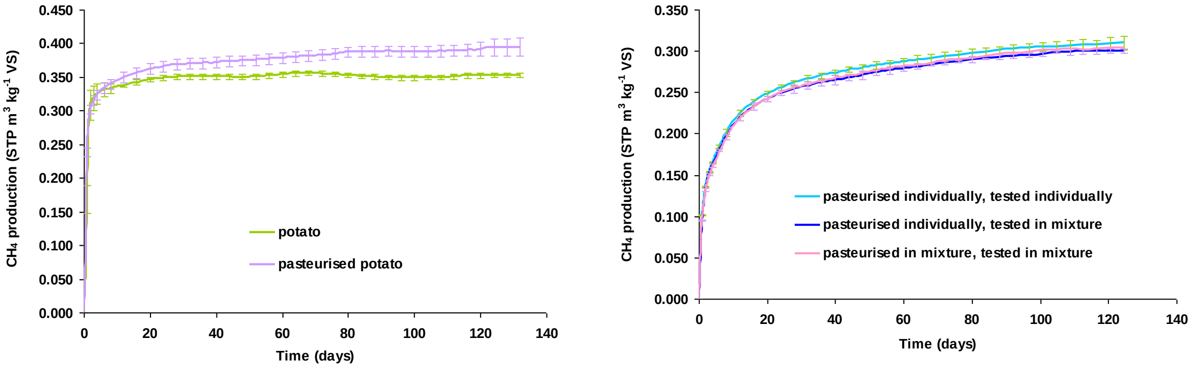
Co-substrates	**Cattle slurry**	**Rumen content**	**Office paper[4]**	**Paper pulp**	**Brewery waste**		**Whey**	**Potato waste**	**Flourmill waste**	**Card packaging**	**Biodiesel by-product**	**Sheep blood**	**Pig gut and floatation fat**			**Poultry litter**
					Spent grain	Yeast							Pig gut	Flotation fat	9:1 Mixture	
Fundamental characteristics for anaerobic digestion																
pH	7.83	7.81	9.1	6.65	4.84	6.18	4.49	8.12	6.26(1:10)	7.21	12.19	7.23	5.85	5.61	5.96	8.89
TS (% WW)	9.31	5.38	96.6	22.2	21.9	14.4	6.07	24.7	88.2	93.9	99.2	19.7	19.9	73.8	20.8	52.8
VS (% WW)	6.52	4.37	76.2	20.5	20.9	12.6	5.48	23.1	84.6	78.5	96.3	18.9	18.5	71.3	19.4	24.3
VS (% of TS)	70	81.2	78.9	92.4	95.3	87.6	90.2	93.2	95.8	83.6	97	95.6	93	96.6	93.2	45.9
TOC (% of TS)	38.9	41.6	36.4	39.3	50.5	42.5	45.9	43.4	46.3	41.6	32.1	42	44.1	-	45.3	25.6
TAN (% of TS)	1.15	0.45	-	-	-	-	-	-	-	-	-	-	-	-	-	0.64
TKN (% of TS)	3.5	2.04	0.12	0.62	3.41	8.78	2.49	1.53	1.5	0.144	<0.05	14.7	8.17	0.53	7.95	3.45
TOC / TKN	11.1	20.7	271	63.6	14.7	4.52	18.4	28	30.8	288	∞	2.85	5.4	-	5.85	6.7
Bio C[1] / TKN	8.15	14.2	215	35.2	11.6	4.51	18.4	27.5	25.7	42.9	∞	2.85	5.27	-	5.58	5.33
CV (kJ g^{-1} TS)	16.75	18.7	13.16	16.1	21.76	19.74	17.72	16.5	18.9	17.18	18.86	22.91	24.85	-	26.21	8.63
Biochemical composition on a VS basis (g kg^{-1})																
Carbohydrates[2]	21.9	63.4	86.5	53	104	244	812	833	497	242	-	7.2	27.1	-	15.8	84.1
Lipids[3]	93.6	25.7	< 10	< 10	107	< 10	36.3	< 10	15.1	< 10	-	< 10	279	-	349	40.4
Crude proteins	276	160	9.8	41.9	224	647	175	103	98	10.8	< 5	965	551	34.3	538	490
Hemi-cellulose	226	310	125	123	335	20.7	-	22	180	113	-	-	51.5	-	46.7	214
Cellulose	96.7	146	636	398	59.8	13.2	-	22.1	109	304	-	-	51.2	-	46.4	69.8
Lignin	226	245	145	286	166	< 5	-	11.2	122	532	-	-	20.5	-	18.6	154
Nutrients on a TS basis (g kg^{-1})																
TKN	35	20.4	1.2	6.2	34.1	87.8	24.9	15.3	15	1.44	< 0.5	147	81.7	5.3	79.5	34.5
TP	8.58	23.4	0.068	3.47	6.19	25.7	7.57	3.59	2.32	0.134	< 0.02	0.835	8.49	-	8.1	21.9
TK	16.7	12.6	0.08	0.1	0.41	31.6	27.2	23.8	10.2	0.221	< 0.02	3.71	11.7	-	10.9	31.4
Potentially toxic elements on a TS basis (mg kg-1)																
Cd	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 1.0	< 0.05	< 1.0	< 1.0	< 1.0	-	< 1.0	1.64
Cr	113	17.7	4.3	24.9	17.7	< 2.0	< 2.0	6.9	11.7	9.1	< 2.0	< 2.0	5.5	-	14.6	66.4
Cu	58.4	12.4	7.4	17	17.6	25.9	< 4.0	9.8	6.1	20.3	< 4.0	6.7	43	-	37.9	56.5
Hg	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.010	< 0.10	< 0.010	< 0.010	< 0.010	-	< 0.010	< 0.010
Ni	44.8	8.6	6	12.1	6.3	< 5.0	< 5.0	< 5.0	< 5.0	4.5	< 5.0	< 5.0	< 5.0	-	6.9	38
Pb	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	2.9	< 10	< 10	< 10	-	< 10	14.3
Zn	231	87.7	5.6	16.4	71.8	29.8	4.2	20.3	27.4	16.2	< 2.0	16.3	259	-	250	447
Elemental analysis % of TS																
N	3.5	2.04	0.12	0.62	3.41	8.78	2.49	1.53	1.5	0.14	< 0.05	14.7	8.17	0.53	7.95	3.45
C	39.2	42.2	36.7	39.5	50.6	42.9	46.1	43.7	46.4	41.6	32.3	42.1	44.3	-	45.6	26.3
H	5.18	5.61	4.97	6.14	7.18	6.53	6.87	7.18	6.94	4.76	7.69	7.33	7.9	-	8.04	3.78
S	0.31	0.19	< 0.05	0.22	0.27	0.54	0.23	0.06	0.13	0.21	< 0.05	1	0.64	-	0.62	0.55
O	23.1	28.5	32.2	33.7	32	29.1	33.3	38.8	37.1	36.9	34.5	27.1	25.6	-	23.3	25.8

[1] Biodegradable carbon = TOC minus lignin carbon. Formula of Lignin chosen as $C_{9.94}H_{12.82}O_{2.94}$.

[2] in equivalent glucose

[3] n-hexane extractable material (HEM)

The materials tested were source-segregated food waste, mechanically-recovered BMW, cattle slurry, card packaging, potato waste, pig gut and flotation fat, and sheep blood. From the results, it was concluded that pasteurisation showed a positive effect only on the methane yield of potato (Figure 3a) and blood. The pasteurisation process had no impact upon the anaerobic biodegradation rate or the extent to which other substrates were degraded. There were also no apparent synergistic or antagonistic effects as a result of the heat treatment (Figure 3b). The results indicated that the option of pre-pasteurising waste streams before feeding to the digester is unlikely to significantly increase or decrease gas production. Therefore, the wastes were used without pasteurisation in the semi-continuous trials.



a) Pasteurised and un-pasteurised potato *b) Food waste and cattle slurry mixes*

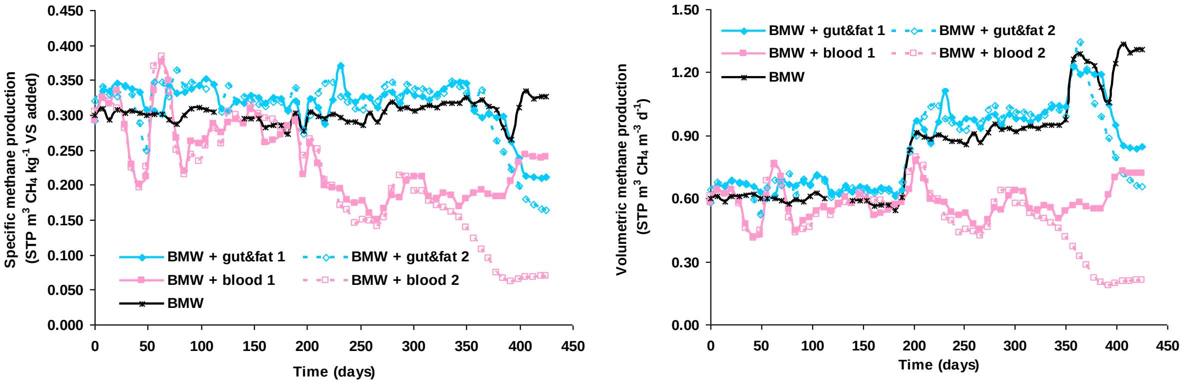
Figure 3. BMP tests on pasteurised and un-pasteurised materials

5 Co-digestion trials

5.1 *Co-digestion with mechanically-recovered BMW (objectives 5 and 6)*

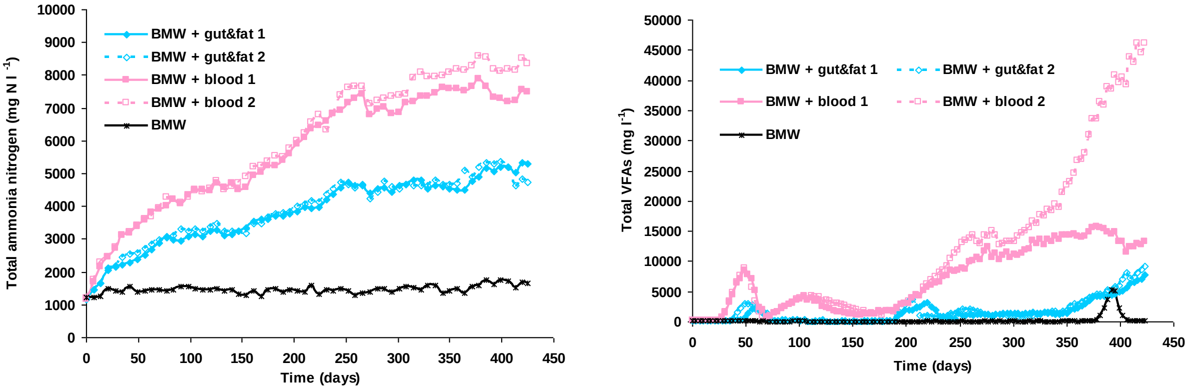
A set of BMP tests was carried out on the mechanically-recovered BMW mixed with each of its four co-substrates (biodiesel by-product, sheep blood, pig gut and flotation fat, and poultry litter), with the co-substrates representing 20% of the total VS in the mix. The BMP values obtained were 0.334, 0.357, 0.358 and 0.329 STP m^3 CH_4 kg^{-1} VS respectively, compared to the previously determined BMP value of 0.344 STP m^3 CH_4 kg^{-1} VS_{added} for mechanically-recovered BMW alone. Using these results a BMP value for the co-substrate could be estimated and compared to the theoretical value and to the result from an actual BMP test on the co-substrate with a sewage sludge inoculum. Blood had the highest estimated BMP of 0.450 STP m^3 CH_4 kg^{-1} VS_{added}, corresponding to 93.5% of the theoretical value, indicating its ready biodegradability. When the BMP for blood was determined as a single substrate with a sewage sludge inoculum, however, a value of 0.418 STP m^3 CH_4 kg^{-1} VS_{added} was obtained, which is lower than the estimated value. Pig gut and flotation fat also had a high estimated BMP of 0.474 STP m^3 CH_4 kg^{-1} VS_{added}, but this corresponded to only 71% of its potential. When determined as a single substrate the BMP value for pig gut and flotation fat was 0.595 STP m^3 CH_4 kg^{-1} VS_{added}, which was considerably higher than the estimate made from the mixed substrate test. The values obtained from the single substrate tests are direct measurements and are therefore more reliable in terms of describing the properties of the material, but the mixed substrate test shows how the material may react in co-digestion. The above results show the difficulties in making predictions of gas production based on batch tests, and confirm the need to carry out continuous or semi-continuous fed simulation tests to obtain accurate gas production data and establish stability criteria.

When BMW was digested with blood as a 20% VS component in the mix in semi-continuous trials at an OLR of 2 kg VS m^{-3} d^{-1} the ammonia rose to 6000 mg l^{-1}, but at this loading the VFA concentration stabilised and the SMP was 0.288 STP m^3 CH_4 kg^{-1} VS_{added} (Figure 4a) compared to 0.357 STP m^3 CH_4 kg^{-1} VS_{added} in the BMP test, i.e. 81% of the measured BMP. Increasing the loading rate to 3 kg VS m^{-3} d^{-1} led to a rise in ammonia concentration to 8000 mg l^{-1} (Figure 4c) and VFA to over 15000 mg l^{-1} (Figure 4d), with an increasing proportion of propionic acid. VFA concentrations in one of the pair of digesters then rose higher still with a substantial fall in methane production. From the perspective of improving the biogas yield there was no advantage in adding blood as a co-substrate in the proportion used (Figure 4b). It may however have some value in improving the nitrogen content of the final digestate product, as blood has an extremely high TKN level of 147 g kg^{-1} TS; the recommendation would be to add blood as a proportion of the mix so as to ensure that the total ammonia concentration in the digester does not exceed 3-4000 mg l^{-1}.



a) Weekly average specific methane production

b) Weekly average volumetric methane production



c) Total ammonia nitrogen concentration

d) Total VFA concentration

Figure 4. Results of co-digestion trial with mechanically-recovered BMW in 4-litre digesters

When BMW was digested with pig gut and flotation fat as a 20% VS component in the mix in semi-continuous trials at an OLR of 2 kg VS m^{-3} d^{-1} the SMP was 0.319 STP m^3 CH_4 kg^{-1} VS_{added} compared to the 0.358 STP m^3 CH_4 kg^{-1} VS_{added} expected from the BMP result, i.e. 89% of the BMP. The SMP of the mix was about 10% greater than for the mechanically-recovered BMW alone. The co-substrate added to the digester TAN and there was some early evidence of VFA accumulation but this later stabilised (Figure 4c and d). An increase in OLR to 3 kg VS m^{-3} d^{-1} showed no reduction in SMP and at this load the VMP reached ~1.0 STP m^3 CH_4 m^{-3} d^{-1} (Figure 4b) with the TAN stabilising at ~4500 mg l^{-1} and VFA concentrations of 1-2000 mg l^{-1}. At the final loading of 4 kg VS m^{-3} d^{-1} the TAN concentration was around 5000 mg l^{-1} and there was a fall in pH, increasing VFA, and a severe drop in SMP. The digesters had not recovered when the trial finished, but the reactor conditions indicated that this was not a safe loading for this mix.

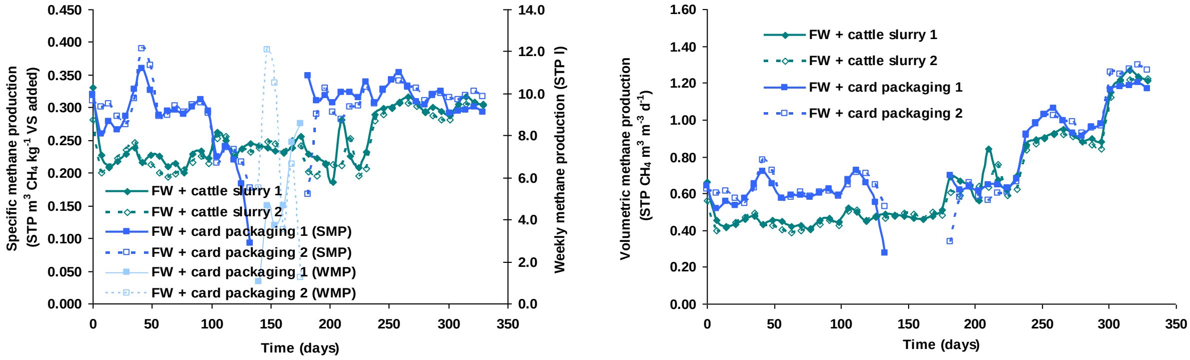
5.2 Co-digestion with food waste (objectives 5 and 6)

In the BMP test using office paper and flourmill waste these co-substrates represented 20% of the total VS, whereas in the mix with whey this was 17% and with cattle slurry 80%. The BMP values obtained were: 0.372, 0.398, 0.403 and 0.264 STP m^3 CH_4 kg^{-1} VS respectively compared to the previously determined BMP of the food waste of 0.445 STP m^3 CH_4 kg^{-1} VS_{added}. All of these co-substrates had relatively low BMP values when estimated from the combined BMP test. The estimated values were: 0.137 (office paper), 0.264 (flour mill waste), 0.267 (whey) and 0.222 (cattle slurry) STP m^3 CH_4 kg^{-1} VS_{added} and the proportion of the theoretical BMP converted was 39, 68, 58 and 59% respectively. It is possible that conversion in this BMP test was hampered by high concentrations of VFA and ammonia present in the food waste digestate used as inoculum, and these values should therefore be treated with caution. The BMP test carried out with pasteurised material used a sewage sludge inoculum, and the BMP for cattle slurry was 0.267 STP m^3 CH_4 kg^{-1} VS_{added} which is higher than the estimated value when the material was tested in a mixture with food waste using inoculum from the food waste digester. The BMP values for potato waste (0.353 STP m^3 CH_4 kg^{-1} VS_{added}) and card packaging (0.266 STP m^3 CH_4 kg^{-1} VS_{added}) were not determined as part of a mix with food waste, and the results therefore could not be compared.

In semi-continuous trials at a 4-litre scale, potato waste was used as a co-substrate for food waste on a 20% VS basis, card packaging at 47% VS and cattle slurry at between 40-80% VS. In all cases the 4-litre trial started with an inoculum taken from the 35-litre food waste digester which was already operating with elevated concentrations of VFA and ammonia. The trial with food waste and potato waste did not succeed in stabilising the digester and ultimately failed, as indicated by a loss of gas production. Although the co-digestion delayed the onset of complete failure it is likely that the proportion of co-substrate in the mix was insufficient to lower the TAN to a non-inhibitory concentration, and the co-substrate itself may not have contributed missing essential elements. The high proportion of readily biodegradable starch may also have led to a further imbalance between VFA production and consumption.

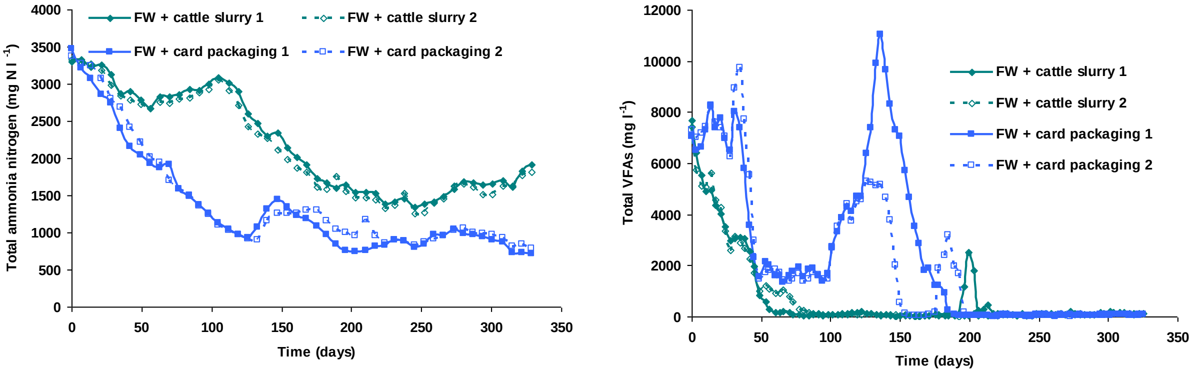
In the trial where cattle slurry was 80% of the mix at a OLR of 2 kg VS m^{-3} d^{-1} the SMP was 0.22 STP m^3 CH_4 kg^{-1} VS_{added}, or 82% of the BMP value (Figure 5a). On decreasing the proportion of cattle slurry to 60% the SMP increased by about 15-20% to ~0.26 STP m^3 CH_4 kg^{-1} VS_{added} but on further increasing the load to 3 kg VS m^{-3} d^{-1} the SMP for this mix was reduced to ~0.23 STP m^3 CH_4 kg^{-1} VS_{added}, reflecting the shorter hydraulic retention time in the digester. The VBP under these conditions was 1.1 STP m^3 m^{-3} d^{-1}, corresponding to a VMP of 0.61 STP m^3 CH_4 m^{-3} d^{-1} (Figure 5b) which was considered acceptable for a commercial AD plant. It would not be possible to increase the loading above this at the mix ratio used without a further reduction in SMP. To increase the SMP without increasing the loading or changing the hydraulic retention time, the proportion of cattle slurry was decreased still further until it represented only 40% VS of the mix. This increased the VBP to ~1.5 STP m^3 m^{-3} d^{-1}. The OLR with this mix was then increased to 4 kg VS m^{-3} d^{-1} and stabilised at a SBP of 0.52 STP m^3 kg^{-1} VS $_{added}$ and a VBP of 2.1 STP m^3 m^{-3} d^{-1}, out-performing that of a single substrate food waste digester. At all the loadings and with increasing proportions of food waste added to the cattle slurry the digester stability parameters of VFA, TAN, pH and alkalinity remained within very safe limits (Figure 5c and d).

A larger-scale 75-litre digestion trial was undertaken with 20:80% VS mix of food waste and cattle slurry at an OLR of 2 kg VS m^{-3} d^{-1} and showed a similar SMP of 0.21 STP m^3 kg^{-1} VS_{added} (Figure 6a). The VBP was between 0.65 - 0.75 STP m^3 m^{-3} d^{-1}, with around 50% of the VS converted to biogas. Ammonia stabilised at around 1500 mg l^{-1} and VFA concentrations were less than 100 mg l^{-1} (Figure 6 c and d). Although the digester was very stable there were some fluctuations in performance due to the use of different batches of cattle slurry: the properties of this material are variable depending on time of year and the diet of the cattle.



a) Weekly average specific methane production

b) Weekly average volumetric methane production



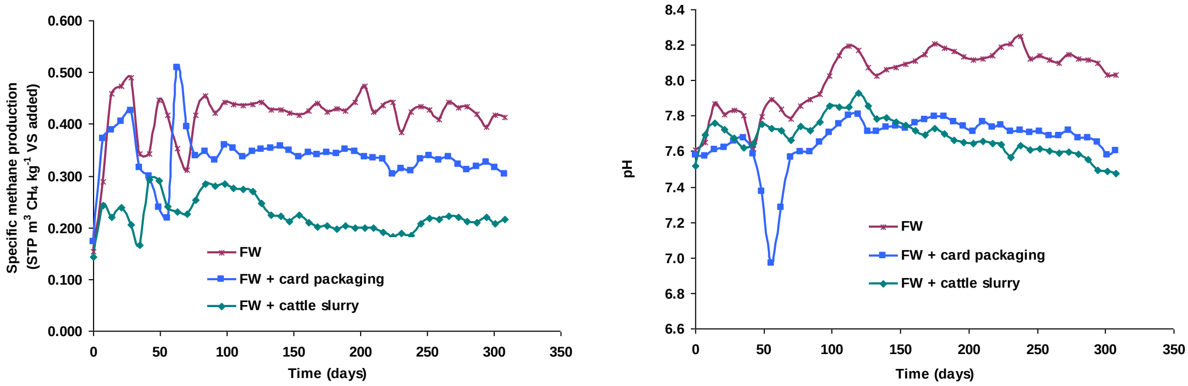
c) Total ammonia nitrogen concentration

d) Total VFA concentration

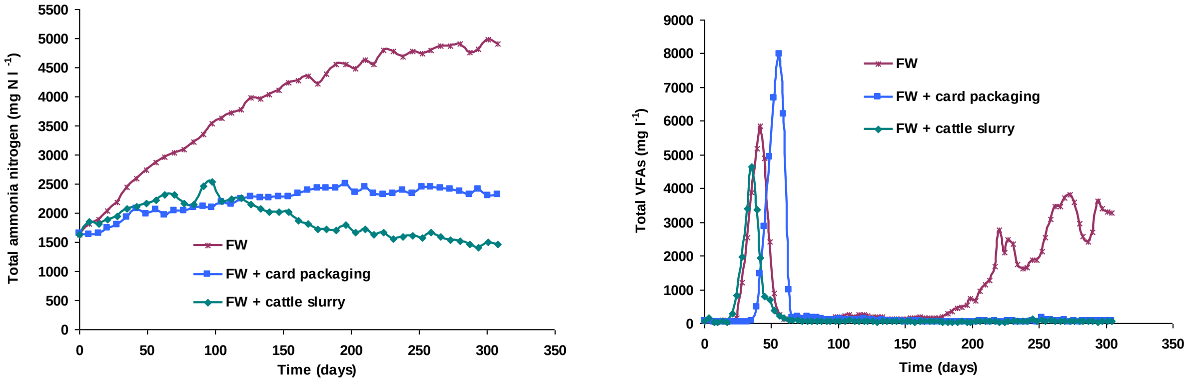
Figure 5. Results of co-digestion trial with food waste in 4-litre digesters

The 4-litre trial with food waste and card packaging on a 53:47% VS basis was able to improve the performance of the inoculum taken from the 35-litre food waste digester, taking about 1-2 retention times to reduce the VFA concentration to around 1500 mg l^{-1} and TAN to around 1800 mg l^{-1}. During this period the methane content of the biogas was about 55%, the SBP fluctuated around 0.54 STP m^3 kg^{-1} VS_{added}, the SMP was 0.31 STP m^3 kg^{-1} VS_{added} (Figure 5a), the VBP 1.1 STP m^3 m^{-3} d^{-1}, and around 70% of VS was converted into biogas. Initially it proved difficult to increase the digester loading without inducing over-production of VFA that could not be buffered by the falling concentration of TAN (Figure 5c and d). On a second attempt, the loading was successfully increased to 3 and then 4 kg VS m^{-3} d^{-1} whilst maintaining a SBP of 0.55 STP m^3 kg^{-1} VS$_{added}$, and an SMP 0.32 STP m^3 kg^{-1} VS which is equivalent to 84% of the additive BMP of the two components of 0.38 STP m^3 kg^{-1} VS. The VBP at this point was 2.2 STP m^3 m^{-3} d^{-1} giving a 55% improvement in performance over that achieved in the digestion of food waste alone.

A larger-scale 75-litre digestion trial undertaken with food waste and card packaging on a 53:47% VS basis at an OLR of 2 kg VS m^{-3} d^{-1} showed a SMP of 0.32 STP m^3 kg^{-1} VS $_{added}$ (Figure 6a) similar to that in the 4-litre trial. The VBP was 1.2 STP m^3 m^{-3} d^{-1} with around 75% of the VS converted to biogas. Ammonia stabilised at around 2400 mg l^{-1} and VFA concentrations were less than 100 mg l^{-1} (Figure 6c and d)



a) Weekly average specific methane production   *b) pH*



c) Total ammonia nitrogen concentration   *d) Total VFA concentration*

Figure 6. Results of co-digestion trial with food waste in 75-litre digesters

6 Digestate characteristics (objective 7 and 8)

6.1 Plant nutrient, PTE and essential element concentrations (objective 7)

The concentration of plant nutrients, potentially toxic elements (PTE) and essential elements for anaerobic digestion was determined in the whole digestates and the separated liquor and fibre fractions. The results for whole digestates are given in Table 3 expressed on a total solids basis, with the limit values for PTE from PAS 110. The values largely reflected those in the corresponding feedstock or mixture. The digestate from mechanically-recovered BMW co-digestion trials was rich in essential elements and also high in PTE; whereas PTE levels in both the food waste co-digestates were well below the upper limits specified in PAS 110

Table 3 Characteristics of whole digestate from mechanically-recovered BMW (BMW) and food waste (FW) trials in semi-continuous digesters

	BMW ^{1}	**FW ^{2}**	**BMW + pig gut and fat ^{3}**	**BMW + sheep blood ^{3}**	**FW + cattle slurry ^{2}**	**FW + card packaging ^{2}**	**PAS 110**
Plant and macro-nutrients (g kg^{-1} TS)							
TKN	34.7	136	54.4	76.5	58.8	65.3	-
TP	4.6	14	6.2	4.0	13	8.9	-
TK	11	50	12.0	11.5	34	25	-

Potentially toxic elements (mg kg^{-1} TS)							
Cd	1.4	<0.50	1.2	1.2	<0.50	<0.50	1.5
Cr	220	79	205	170	31	53	100
Cu	380	130	380	380	100	160	200
Pb	470	18	435	400	<10	52	200
Hg	0.65	<0.25	0.6	0.6	<0.25	<0.25	1.0
Ni	120	48	103	98	16	29	50
Zn	810	180	710	800	270	130	400
Essential elements (mg kg^{-1} TS)							
Co	12	<1.0	10	10	<1.0	<1.0	-
Fe	8800	5700	7500	7450	<2000	3200	-
Mo	8	5.2	8	7	3.9	5.4	-
Se	0.51	0.7	0.60	0.48	<0.30	<0.30	-
W	<1.0	<1.0	<1.0	<1.0	<1.0	<1.0	-
Solids content (% WW)							
TS	16.3	6.04	18	14	5.84	6.76	-
VS	7.47	4.19	8.91	8.20	4.38	4.45	-
VS %TS	45.8	69.4	49.2	57.6	75.1	65.8	-

[1] 4-litre digester trials [2] 75-litre digester trials [3] Average of 2 4-litre digesters

6.2 Digestate Stability (objective 8)

The biostability of digestates was determined based on the residual biogas production, and two methods were used for this purpose: the BMP method described in Appendix 1 of the main Technical Report, and the BM100 method as specified in the Environment Agency's Guidance on monitoring MBT and other pre-treatment processes for the Landfill Allowances Trading Scheme (England and Wales) 2005. The BMP tests were carried out in-house, and duplicate samples of digestate fibre from the larger-scale digester fed on food waste and card packaging were sent to an accredited laboratory for BM100 testing after pre-preparation according to the test specification. In addition to this sample the mixed food waste and card packaging co-substrate and a cellulose control were also tested.

There is currently no approved stability standard against which these results can be compared to ascertain whether a satisfactory degree of stabilisation has been achieved. From the BMP test results, the residual methane production of digestate from mechanically-recovered BMW and from food waste and card packaging was only around 0.100 STP m^3 kg^{-1} VS during the 100-day tests. This was as expected because the digestates were taken from well-functioning digesters running at a moderate loading rate. Digestate fibre from the digester fed on food waste and cattle slurry had a relatively high residual methane potential of 0.196 STP m^3 kg^{-1} VS; this was because cattle slurry contains a relatively high proportion of lignocellulosic materials which are only slowly degraded, and since the material also has a high water content it has a relatively short retention time in the digester. Digestate liquor from the digester fed on food waste and cattle slurry had a lower residual methane potential (0.093 STP m^3 kg^{-1} VS) than the digestate fibre, perhaps due to the lignocellulosic materials in the fibre component. Food waste digestate had the highest residual methane potential of 0.203 STP m^3 kg^{-1} VS; this was probably because the larger-scale food waste digester had VFA concentration of 2600 mg l^{-1} when the digestate sample was taken on day 286.

The 100-day biogas production values from the BMP tests were 0.675 and 0.180 STP m^3 kg^{-1} VS for mixed food waste and card packaging co-substrate and digestate fibre respectively, considerably higher than the values of 0.420 and 0.102 STP m^3 kg^{-1} VS given by the BM100 test. The biogas production of cellulose in BM100 test was only 0.417 STP m^3 kg^{-1} VS, which is half its theoretical value of 0.830 STP m^3 kg^{-1} VS.

It is clear that the results for residual biogas or methane potential are very dependent upon the method used. The BMP procedure carried out at Southampton showed smooth biogas and methane production in the initial stage of the test, and consistency between replicates throughout the test; the biogas and methane potential of the reference material cellulose was 0.815 and 0.409 m^3 kg^{-1} VS respectively, or 98% of the theoretical values.

As a further check on the BMP test a simple biogas mass balance was carried out based on the volatile solids removal and the specific biogas production (SBP) of the larger-scale digester fed on food waste and card packaging. This should show good agreement with the difference between the input (food waste and card packaging mixture) and output (digestate fibre) values. The value of 0.622 STP m^3 kg^{-1} VS obtained from the test results was only 5% different from the SBP, indicating that SBP could be used as a method of assessing stability in commercial digesters.

7 Overall conclusions and suggestions

The research was not designed to consider the economics or engineering design features of anaerobic digestion plant. In making suggestions, however, some factors that might impinge on these are considered. For example the volumetric biogas potential (VBP) of a plant is of major economic importance at it determines the ratio of production of saleable energy to the capital investment made in the volumetric capacity of the plant. The situation is now more complicated due to energy subsidies and gate fees, but historically it was accepted that a VBP of at least 1 STP m^3 m^{-3} d^{-1} should be achieved and a value of 2 STP m^3 m^{-3} d^{-1} would be a very attractive investment. The methane production per tonne of wet waste is also important as this will have some influence on the distance over which it can be transported. A value of 100 m^3 CH_4 $tonne^{-1}$ is potentially a very good substrate, whereas one at 20 m^3 $tonne^{-1}$ should only be used where transport requirements are minimal. The specific methane productivity (SMP) is related to the feedstock and is the proportion of the biochemical methane potential (BMP) that is achievable in continuously operating plant. The SMP should ideally be no less that 80% of the BMP. There is no ideal plant nutrient balance in a digestate as fertiliser requirements depend on soil type and crop being grown. A typical fertiliser for use on productive grass land would have an N:P:K ratio of 100:20:20, for spring cereals of 100:40:50, and for potatoes 100:100:100.

Mechanically-recovered BMW

- Mechanically-recovered BMW is a good substrate for anaerobic digestion and it should be possible to achieve a volumetric biogas productivity (VBP) of 2.2 STP m^3 m^{-3} d^{-1} at a loading rate of 4 kg VS m^{-3} d^{-1}. This loading should be achievable in a 'wet' completely mixed single stage digester that will operate at a TS content in the digestate of around 17%. The methane yield of material on a wet tonne basis is 110 m^3 $tonne^{-1}$.
- Mechanically-recovered BMW is probably also suited for digestion in a 'dry' type digester at a higher loading and volumetric gas productivity, but this was not investigated as part of the current research. Further work is needed to establish if 'dry' digestion systems have benefits compared to 'wet' systems when applied to waste streams of this type.
- The Nitrogen, Phosphorus and Potassium (NPK) ratio of the mechanically-recovered BMW digestate was 100:12:32 in digestate liquor, 100:26:34 in digestate fibre and 100:13:32 in whole digestate.
- The mechanically-recovered BMW digestate liquor exceeds the PAS 10 limit for the potentially toxic elements (PTE) Cd, Cu, Ni, Pb, and Zn. The digestate fibre exceeds the PAS 110 specification for the metals Cr, Cu, Ni, Pb and Zn. While this does not rule out land application for non-agricultural purposes, together with the presence of plastics and other physical contaminants it limits the potential of the material as a high-value product.

Source-segregated food waste

- Food waste has a very high specific methane yield of 0.425 STP m^3 kg^{-1} VS_{added} which is equal to 93 m^3 CH_4 $tonne^{-1}$ on a wet weight basis.
- The high nitrogen content of food waste results in a high digester total ammonia nitrogen (TAN) and this can lead to raised concentrations of volatile fatty acids in the digestate. The overall loading may be limited by the unusual fermentation conditions that develop and the restricted microbial consortium that can adapt to these conditions. The maximum loading achieved in this research with food waste as a single substrate was 2 kg VS m^{-3} d^{-1}
- Ideally the digestate TAN should be reduced to a level where it is non-toxic to the acetoclastic methanogenic population. This is probably less than 4000 mg l^{-1} but is dependent on pH and other factors. Further research needs to be carried out to assess methods of reducing digester ammonia levels and to provide a better understanding of the impact of high ammonia concentrations on the syntrophic communities in the digester. (See also sections below on co-digestion).
- Food waste is probably lacking in essential trace elements and these need to be added to prevent the accumulation of VFA, and in particular of propionic acid. Trace elements likely to be deficient are Selenium and Cobalt. Other trace elements such as Molybdenum and Tungsten may also be important in mediating essential metabolic pathways when acetoclastic methanogens are inhibited by high digestate TAN. Further research is needed to establish the required trace elements and the correct dose rate.
- The maximum VBP that could be achieved with food waste at the limited loading of 2 kg VS m^{-3} d^{-1} was 1.4 STP m^3 m^{-3} d^{-1}.
- The NPK ratio of food waste digestate was 100:10:36 in digestate liquor, 100:21:39 in digestate fibre, and 100:10:37 in whole digestate.
- Food waste digestate liquor and fibre were both within the PTE specification of the proposed PAS 110.

Co-digestion with mechanically-recovered BMW

- Co-digestion with mechanically-recovered BMW is possible with a number of waste materials, but for the two tested no improvement was obtained in the VBP.
- Co-digestion may restrict the achievable process loading if substrates are too rich in total Kjeldahl nitrogen (TKN) or lipids.

- The greatest potential advantage of co-digestion with mechanically-recovered BMW is to alter the nutrient balance in the digestate, improving its potential for use in land reclamation and other non-agricultural applications such as forestry and long-term cultivation of non-food crops.

Co-digestion with source-segregated food waste

- Co-digestion of food wastes offers the potential for reducing the TAN concentration in the digester allowing stable operation at higher loadings. The VBP achieved with a mix of food waste and card packaging at an OLR of 4 kg VS m^{-3} d^{-1} was 2.2 STP m^3 m^{-3} d^{-1}, which was a 54% improvement in performance over that achieved by digestion of food waste alone. Co-digestion of food waste and cattle slurry on a 60:40% VS basis at an OLR of 4 kg VS m^{-3} d^{-1} gave a VBP of 2.1 STP m^3 m^{-3} d^{-1}, which out-performs a single substrate food waste digester by 45%.
- The 60:40% VS mix of food waste to cattle slurry (about 2:3 on a volume basis) gave a very good VBP of 2.1 STP m^3 m^{-3} d^{-1}, but does not correspond well with the relative amounts of these materials produced in the UK at present. A 40:60% VS mix is about 5:1 on a volume basis, which is more representative of the proportions produced in the UK. This gave a VBP of 1.13 STP m^3 m^{-3} d^{-1}, which is acceptable for a commercial AD plant. It would therefore make good sense to blend food waste with cattle slurries, raising the volumetric productivity from less than 1 to potentially more than 2 STP m^3 m^{-3} d^{-1} making slurry digestion economically feasible.
- Card packaging can be recommended as a co-substrate for food waste digestion. This mixture has a similar biochemical composition to mechanically-recovered BMW with a moderate TKN concentration, but without the physical and chemical contaminants present in mechanically-recovered BMW. Apart from lowering the overall TKN of the feedstock mixture, card packaging also brings some essential elements into the digester to ensure the function of autotrophic methanogens. It is possible however that the plastic content in some card packaging may make the digestate less attractive as a quality product.

General

- There is a need for a catalogue of waste types suitable for co-digestion with characterisation data so that the impacts of blends on the digestion process and the quality of the digestate can be estimated.
- The key parameters for stable digester operation and/or digestate quality are: TKN, C:N ratio, lipid content, and trace element profile and PTE concentration.
- The biochemical methane potential (BMP) obtained in practice cannot be reliably estimated either from the Buswell equation or from a knowledge of the biochemical characteristics of the waste; BMP values have to be determined experimentally.
- In semi-continuous studies with continuously stirred tank reactor (CSTR) digesters SMP was generally around 80-85% of BMP values at the loading rates achieved.
- There is currently no agreed method for testing the stability of digestate for land application, although it is likely that a method based on residual methane potential will be adopted for PAS 110 and a standard of acceptability defined. Tests carried out in CSTR digesters to assess the residual methane potential of the baseline waste streams and co-substrates gave values in the range of 0.09-0.20 STP CH_4 m^3 kg^{-1} VS_{added}.

References to published material

9. This section should be used to record links (hypertext links where possible) or references to other published material generated by, or relating to this project.