

CO-DIGESTION - ENHANCING RECOVERY OF ORGANIC WASTE*B. Purcell¹⁾ and E. I. Stentiford²⁾***1) WS Atkins, Woodcote Grove, Ashley Road, Epsom, Surrey, KT18 5BW, UK****2) School of Civil Engineering, The University of Leeds, Leeds, LS2 9JT, UK****1. ABSTRACT**

Laboratory scale trials were carried out to anaerobically digest mixtures of biodegradable supermarket wastes and sewage sludge. 8 reactors were used, each 20 litres capacity operated mesophilically (35°C) The results showed that increasing organic loading rates from 2.5gVS/l.d to 6.0-6.5gVS/l.d resulted in a three-fold increase in biogas generation. Further increases in organic loading rates to 7.6gVS/L.d. promoted considerable deterioration in the performance of a number of the digesters. Digester performance was restored rapidly with the addition of an alkali to increase reactor pH to around neutral values. Digestate from both primary and co-digestion cells indicated valuable NPK concentrations, with digestate from co-digestion containing lower PTE concentrations for beneficial use.

2. INTRODUCTION

By 2020, the management of household, commercial and industrial wastes is likely to be considerably different than today's waste management operations. Greater amounts of organic wastes will be recycled for beneficial use through increased composting and anaerobic digestion schemes. The development of energy from waste plants will provide a greater capacity to recover energy from household wastes; and landfill will have become increasingly more engineering providing treatment and disposal for a number of controlled wastes.

These likely changes in operational practices will be driven at the European level by the implementation of the EC IPPC and Landfill Directives. Different states within the EU will embody the Directives within their own regulations. For example in the UK the recently published waste strategy aims to reduce the amount of waste disposed to landfill in England and Wales and increase the levels of waste recycling and composting (DETR, 2000).

Alternative technologies for the management of organic wastes include the use of anaerobic digestion of organic wastes, however, currently there are no commercially operating large-scale plants in the UK. A number of AD schemes in the UK have failed to develop commercially because of contaminated feedstocks (crude MSW) requiring high processing costs; and a resulting contaminated, poor quality digestate of low market value end use. The use of anaerobic digestion may be particularly suited for the co-treatment of high moisture content organic wastes (commercial and industrial wastes) and sewage sludge in the UK. Supermarket produced wastes, for example, have been shown to have moisture contents in the 82-88% range and are readily degradable under anaerobic conditions (Purcell & Stentiford, 2000).

3. ANAEROBIC DIGESTION & CO-TREATMENT

The amount of organic residuals stabilised through anaerobic digestion (AD) has been estimated at over 1M tonnes per annum (wet wt.) worldwide (Mata-Alvarez *et al.*, 1999; Anon, 1999). The majority of the plants in operation (62%) favoured mesophilic over thermophilic conditions with 90% of all plant operating as single stage digestion systems (Anon, 1999). However, the current cost estimates for AD, at 1.2-1.5 times higher than composting, may continue to restrict the development of large-scale commercial facilities in the UK (Mata-Alvarez *et al.*, 1999; Hawkes, 1999; IWM, 1998).

Experimental trials, to date, have provided valuable performance data on both the digestion of MSW and on co-digestion with sewage sludge. Cecchi *et al.* (1990) investigated the effect of increasing organic loading rate (OLR) on biogas generation and total solids destruction. Using 3m³ anaerobic digesters to treat organic fractions of MSW, experimental data showed no deterioration in digester performance as the OLR was increased from 3.4 to 6.8kg/m³.d at hydraulic retention times (HRT) of 15-32 days. Solids destruction was determined at 25-30% with specific gas production rates of 0.23-0.28m³/kgVS added (methane concentrations 50-64% (v/v)). In later work, Cecchi *et al.* (1992) operated anaerobic digesters treating organic fractions of MSW under semi-dry conditions and found that stable conditions were achieved at considerably lower HRTs of 6 days (OLRs up to 20kgVS/m³.d).

Investigating the potential of co-digestion, Peres *et al.* (1992) carried out work using 8L reactors treating organic fractions of MSW and primary sewage sludge. The reactors were operated at OLRs ranging from 1-3.8gVS/L.d at 7% DS feed sludge, 73% volatile solids, and operated at 20 days HRT. The results showed a TS destruction rate of 54-57%

with a volatile solids destruction rate of 58%. Specific gas production range from 0.34-0.37L/g VS added with methane production from 0.21-0.23L/gVS added. Average gas composition was 62% methane and 38% carbon dioxide.

The biological methane potential of MSW components (digestion feedstock) including paper, plastics, yard wastes and cardboard was investigated by Owen & Chynoweth (1993). Results from their study indicated similar methane yields to Peres *et al.* (1992) of 0.19 to 0.22m³CH₄/kg VS added.

In full-scale work, Fruteau de Laelos *et al.* (1997) described the Valorga AD process experience at a full-scale plant in Tilburg, Netherlands. The plant was designed to treat 52,000 tonnes of organic municipal solid waste separately collected. The Valorga process involves an anaerobic semi-continuous, high solids, one-step, plug-flow digestion process. Methane generation from the plant varies from 210-290m³/tonne VS. Digesters are fed at 20% DS at a HRT of 21 days, although depending on plant throughput, HRTs may increase to 55 days. Stable digester VFA concentrations are found at approximately 1,700mg/L (mainly acetic acid), which reflects a high solids system. In contrast, Peres *et al.* (1992) found VFA concentrations of 40-160mg/L.

Other full-scale work reported by Chhabria (2000) describes the Wabio anaerobic digestion process treating 65,000 tonnes per annum of source separated household waste in Bottrop, Germany. Performance data from the plant that has been operating since 1995 showed a VS destruction rate of 57.5% and generates 17MW of power.

Operational experience of AD in Finland, since 1990, was reviewed by Rintala and Jarvinen (1996). Using the Stormossen biogas digester, OLR were found to range from 2.5-4.1kgVS/m³.d. DS content of the MSW was 45% and sludge was 14%. Batch assays showed methane recoveries of 310 and 220 l/kgVS for MSW and SS respectively, the full-scale plant achieves 90% of the batch assay methane recovery. pH values were 7.6; total solids 5.3%, alkalinity 7,600mg/L and VFAs 285mg/L

The first AD plant in Sweden, was designed at 9,000 tonnes per annum in Boras and has been described by Ecke and Lagerkvist (1999). Organic fractions were reduced in size to 40mm. Power generation from the gas produced amounted to 600kWh/tonne of digestibles treated. Operational parameters reviewed included temperature which ranged from 25 to 35° C, HRT from 1.5 to 4 days and total solids loading from 3 to 7% of dry solids..

The co-digestion of organic wastes with sewage sludge using existing water company digestion assets would provide a number of financial and environmental advantages over conventionally operated AD plants including:

- the use of the existing water company asset base will significantly reduce scheme development costs and capital expenditure, maximise assets utilisation and increase the generation of non-regulated revenue;
- combined anaerobic digestion will stabilise organic matter, recover biogas for electricity generation in CHP plants and produce an end product suitable for beneficial use in agriculture and land reclamation (probably following aerobic stabilisation);
- it will use wastes (fruit, vegetables and bakery waste) with high moisture content (82-88% w/w) which are suited to low solids anaerobic digestion; and
- co-treatment schemes will provide an additional waste management strategy for the achieving EC Landfill Directive targets providing a market is established for the digestate

To investigate this potential, a laboratory-scale project was set up to evaluate the benefits of co-digesting sewage sludge and organic wastes. The project was funded by landfill tax credits made available by Waste Recycling Group plc through Waste Recycling Environmental (WREN). The aims of the project were to determine the effects of blending supermarket produced waste with sewage sludge on biogas yield and composition, VS destruction rates and digester stability. The resulting stabilised digestate from both the control and co-digestion reactors was characterised for fertiliser value and potential toxic element (PTE) concentrations.

4. EXPERIMENTAL TRIALS

A total of 8 reactors were operated and comprised 4 control reactors and 4 co-digestion reactors. All 8 digesters were contained in a water bath maintained at 35° C using a heat pump at a 20 day hydraulic retention time (HRT). The reactors were constructed from a 20L (nominal volume) glass vessel with quick-fit glassware attachments. Externally mounted electrical stirrers were used with paddle mixers to provide continuous mixing. The general conditions pertaining to the reactors are shown in Table 1 and their arrangement is shown in Figure 1.

Reactor No.	Description	HRT (days)	Operational temperature ° C
1A	control reactor	20	35
1B	control reactor	20	35
2A	co-digestion reactor	20	35
2B	co-digestion reactor	20	35
3A	co-digestion reactor	20	35
3B	co-digestion reactor	20	35
4A	control reactor	20	35
4B	control reactor	20	35

Table 1. Details of reactor operation for co-digestion trials



Figure 1. 20L reactors using in the co-digestion experimental trials.

The feeding regime adopted for the control and co-digestion reactors was a single daily feed (and exit sludge sample) delivered manually. This method proved the most reliable throughout the operation of the digesters. The potential adverse affect of using this method was the ingress of air during feeding and sampling and the concomitant deterioration of gas production. This potential impact was evaluated at the start of the project and it was found that following feeding, gas production returned rapidly in all digesters (measured using continuous water displacement meters).

Analysis of the exit digestate was carried out 3 times a week and included: dry solids, volatile solids, pH and alkalinity. Temperature, biogas generation and biogas composition for the reactors were measured regularly. VFA concentrations were determined in the reactors on a regular basis (monthly) and more frequently when instability in a number of the co-digestion reactors was noted.

The control cells were fed with primary sludge (largely domestic input) from Mitchell Laithes wastewater treatment plant, West Yorkshire (Yorkshire Water), UK. The primary sludge was collected twice a week and had a typical dry solids concentration in the range 4.5-5.8%.

The co-digestion cells were fed with a combination of supermarket organic wastes and primary sludge. Supermarket wastes (fruit, vegetable and bakery waste) were collected weekly from a local supermarket and homogenised prior to feeding using a food blender (screened less than 8mm). The homogenised waste was blended with primary sludge to produce the required organic loading rate. Details of the physical and chemical primary sludge and co-digestion feed sludge are described in Table 2.

Parameter	Primary sludge	Co-digestion feed sludge
Total solids (% average)	5.6	9.4
Volatile solids (% average)	71.7	81.4
Density (kg/m ³)	990	1010
pH (average)	5.28	5.03
Total VFA (mg/l)	4850 - 5470	5,670 - 6760
Total nitrogen (% DS)	4.4	3.8
Total phosphorus (% DS)	1.2	0.7
Total potassium (% DS)	0.3	1.7
Heavy metals (mg/kg dry wt)		
Cd	1.0	1.0
Cr	160	60
Cu	250	80
Hg	1.0	0.3
Pb	230	70
Zn	1100	440

Table 2. Physical and chemical parameters of the primary sludge and co-digestion mixed feedstock.

5. DIGESTION PERFORMANCE

5.1 Total solids destruction

The destruction of dry solids in both control and co-digestion reactors are shown in Figure 2. The fluctuations in the performance related to the changing dry solids (DS) content of the primary sludge. Initially, the high apparent destruction rates result from gradual wash-out of the seed digested sludge used in the start-up of the reactors. Further increases in DS destruction rates were observed in the co-digestion reactors in contrast to the control reactors where destruction rates fluctuated around 30%. Figure 3 illustrates how the increases in feed sludge DS concentrations had negligible effect on dry solids concentrations in the exit sludge.

Average destruction rates for DS were 27.7% (standard deviation at 13%) for the control reactors. The high standard deviation was attributed to high fluctuations in feed sludge DS concentrations. The performance of the co-digestion reactors produced a significantly higher destruction rate of 53.7% with a similar standard deviation of 12%. This substantial increase was related to a greater OLR and a more degradable feed sludge (fresh fruit, vegetables and bakery wastes). Similarly, VS destruction rates for the control reactors were averaged at 36.9% (standard deviation 12%). The co-digestion reactor, however, produced an average destruction rate of 62.9% (standard deviation 12%), considerably higher than for primary sludge digestion but consistent with results report elsewhere (Dunn *et al.*, 1993).

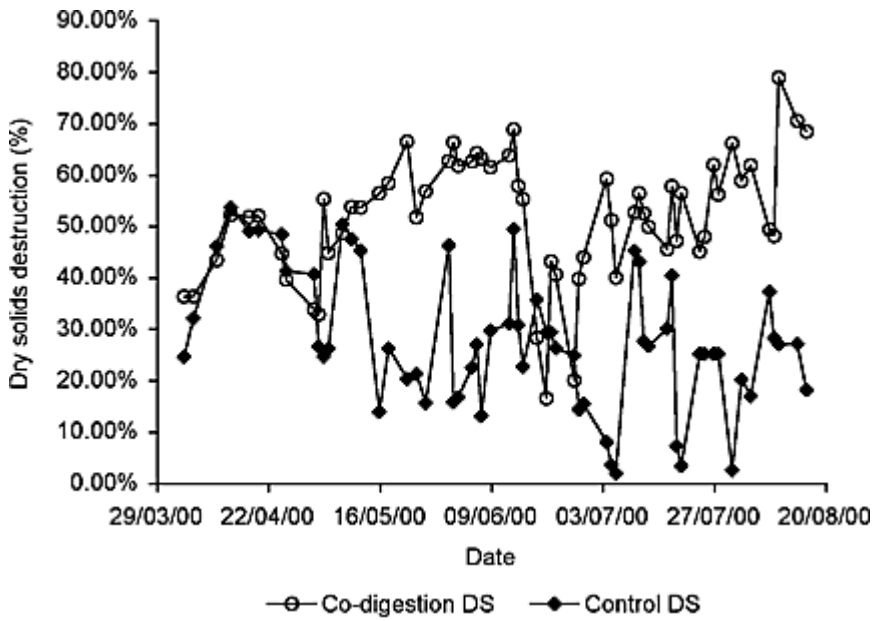


Figure 2. Dry solids destruction in control and co-digestion reactors

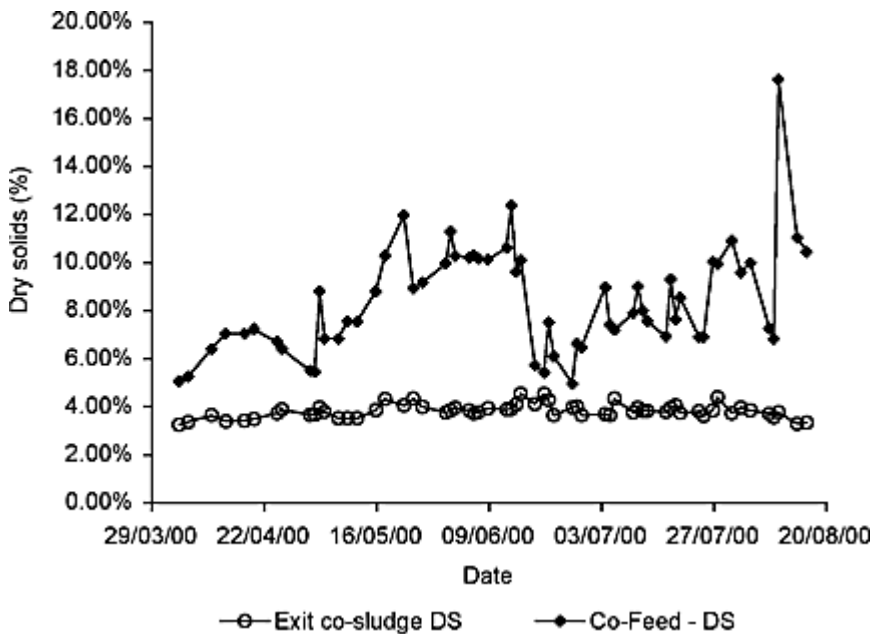


Figure 3. Feed and exit sludge DS concentrations from co-digestion reactors

5.2 Organic loading rates

The organic loading rates for control and co-digestion reactors are shown in Figure 4. The results indicate an initial period of stabilisation where all reactors are fed primary sludge sampled every three days. The variations in OLR are promoted by a fluctuation in dry solids (DS) concentration of the primary sludge which results from operational practice at the wastewater treatment works.

Following a period of stabilisation, the OLR for the co-digestion reactors was increased from approximately 3gVS/L up to 4.5-5gVS/L and further to a peak of 7.6gVS/l in a step-wise manner. The fluctuation in the feed concentrations was due to changing DS in the primary sludge and the experimental challenges of rapidly determining moisture content at the time of waste blending. Other workers have used similar OLRs for the anaerobic digestion of organic fractions of municipal solid waste (Rintala & Jarvinen, 1996; Peres *et al.*, 1992; Cecchi *et al.*, 1990).

Following the peak of 7.6gVS/L, the OLR was decreased as a number of reactors exhibited methane inhibition from organic overloading (methane concentrations decreased from 65% to 5% v/v, and substantial drops in both pH and alkalinity were noted). To ameliorate the souring digesters, organic loading rates were decreased temporarily and with

the addition of an alkali, stable digestion conditions were re-established within 2 weeks. The OLR was then increased gradually throughout the project to 5.5-6gVS/L with a final peak of over 10gVS/L with no deterioration in digester performance.

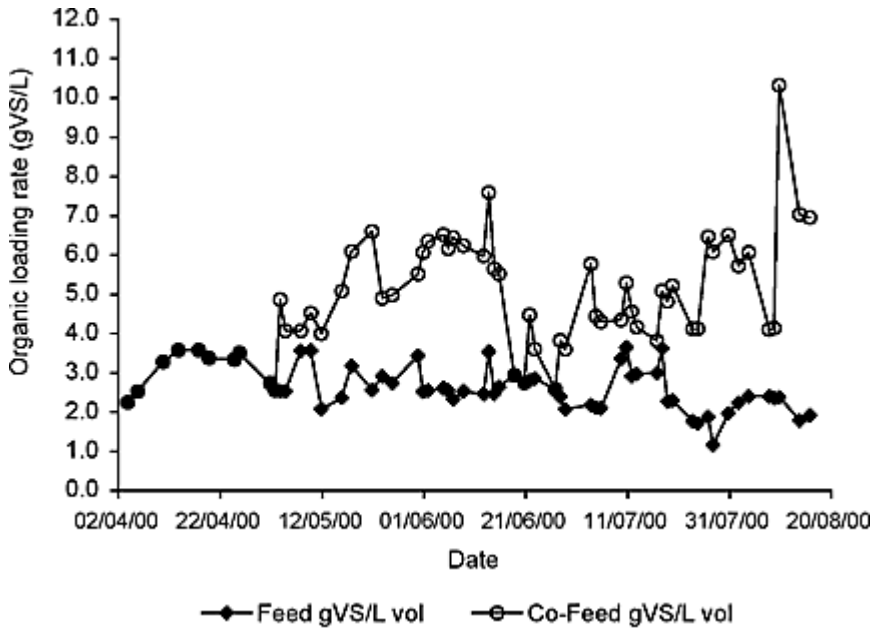


Figure 4. Organic loading rates for control and co-digestion reactors

5.3 Gas production & composition

Gas composition for the co-digestion reactors was more variable than for the control reactors, typically 60-65% CH₄ and 35% CO₂ (Figure 5). The fluctuations in methane concentrations observed over the project duration, result from the varying nature of the co-feed sludge. Throughout the trials, a variety of supermarket wastes were combined with primary sludge including fruit, vegetables and bakery wastes. Attempts were made to provide a consistent blend of supermarket wastes but inevitably variations in the feed sludge were experienced largely in response to the waste production at the supermarket store (average VS in co-feed 83%). These variations in feed sludge, both in terms of overall composition and DS, are likely to have had the greatest impact on the gas composition.

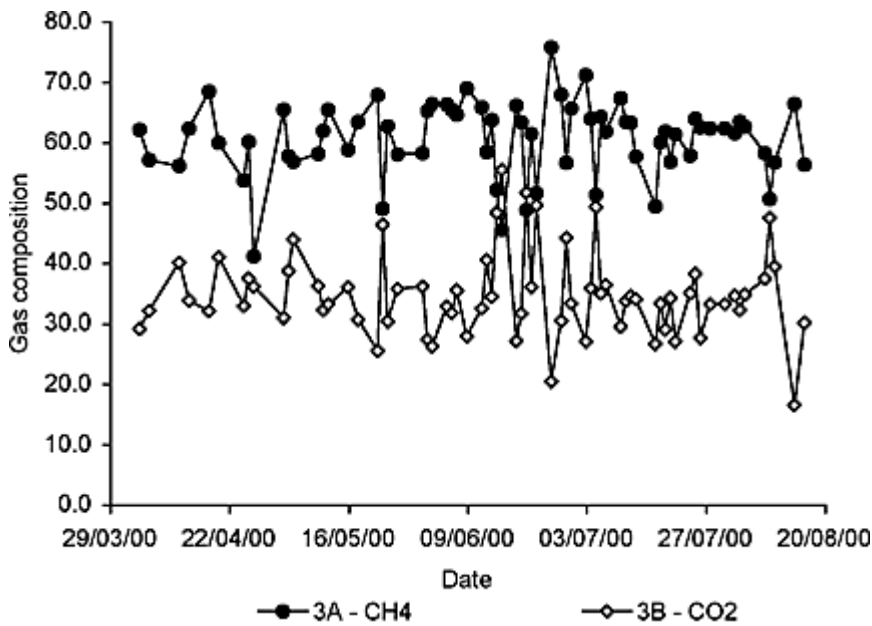


Figure 5. Gas composition in co-digestion reactor 3A

In contrast to Figure 6, gas composition data in Figure 5 shows inhibition during May and June in co-digestion reactor 2B. Methane concentrations reduce dramatically from approximately 60% to 3-5%, while carbon dioxide concentrations increase from approximately 35% to up to 80%. The cause of this inhibition was associated with an increase in organic

loading from 6-6.4gVS/L to 7.6gVS/L. The reactor pH reduced from neutral conditions to pH 4.5-5.0 and VFA concentrations increased rapidly (Figure 6).

Previous work has shown that the inhibition of methanogenesis is affected more by low pH conditions than high VFA concentrations. Other workers have suggested that low pH values greatly enhance the inhibitory effect at high substrate concentrations because of the much higher unionised substrate concentrations (Andrews, 1978). Mosey *et al.* (1993) noted that high concentrations of VFAs were an indication rather than a cause of inhibition of digestion.

The imbalance between VFA production and consumption is shown in Figure 7 where concentrations increase from approximately 100mg/L to 16,500mg/L. Following the addition of an alkali (sodium hydroxide) for several days, the VFA concentrations reduced rapidly to 4,000mg/l and continued to decrease to stable background concentrations.

To restore methane production in 2B, feeding was stopped and fresh exit sludge from the stable control reactors was used as feed for 2B. This strategy continued for approximately 10 days but no significant improvement in methane generation was noted. Sodium hydroxide was added as a 3M solution over several days until the pH changed from around 5 to neutral. Within three days, methane composition had increased to 60% and carbon dioxide concentrations had reduced to 35-40%.

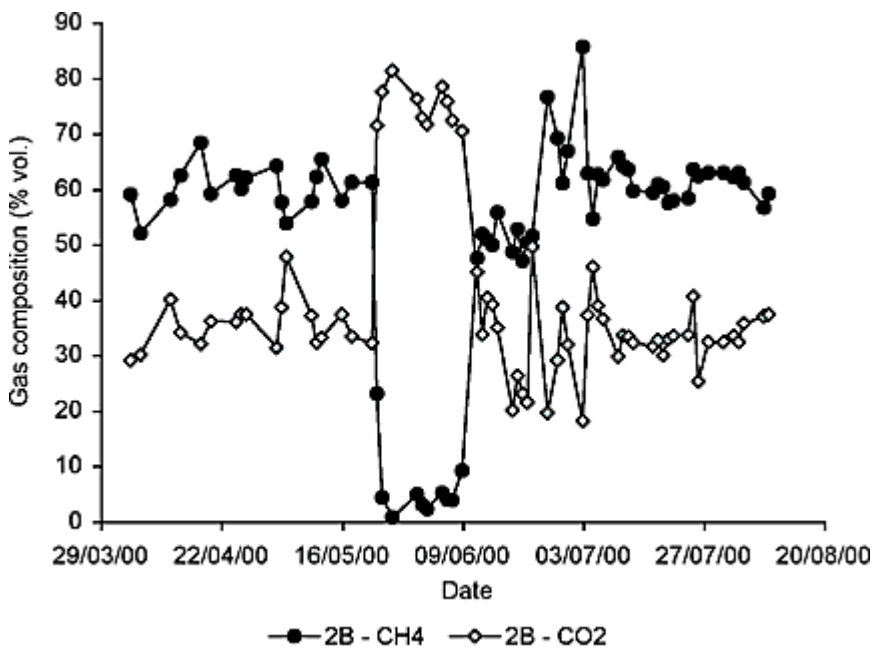


Figure 6. Gas composition in reactor 2B during organic overloading

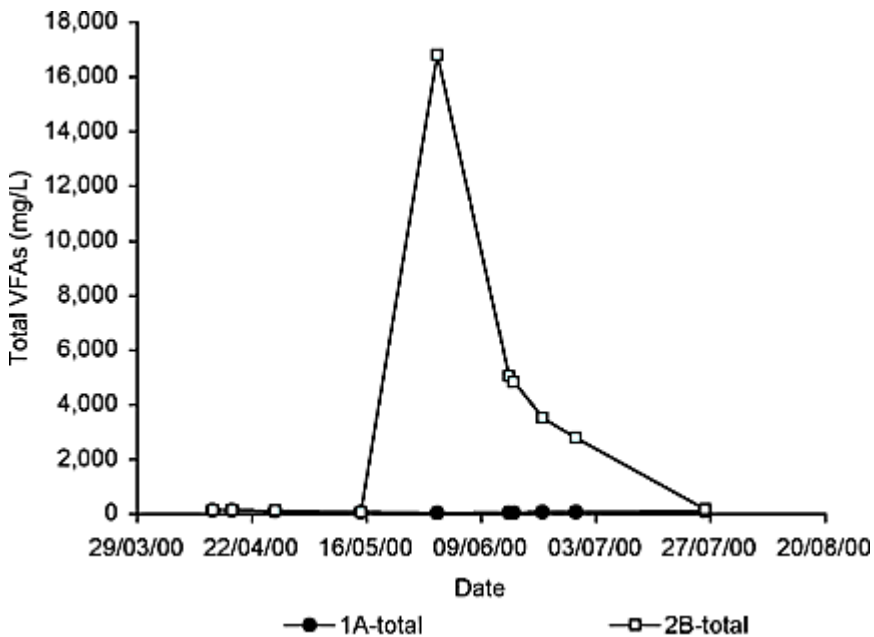


Figure 7. Total VFA concentrations in control (1A) and co-digestion (2B) reactors

Daily gas production data is presented in Figure 8 and illustrates the effects of sludge feeding on gas production (single daily feeds). The peak gas production (measured over a period of 30 minutes with a low flow gas meter) from co-digestion reactors is observed at greater than six times the peak production from the control reactors.

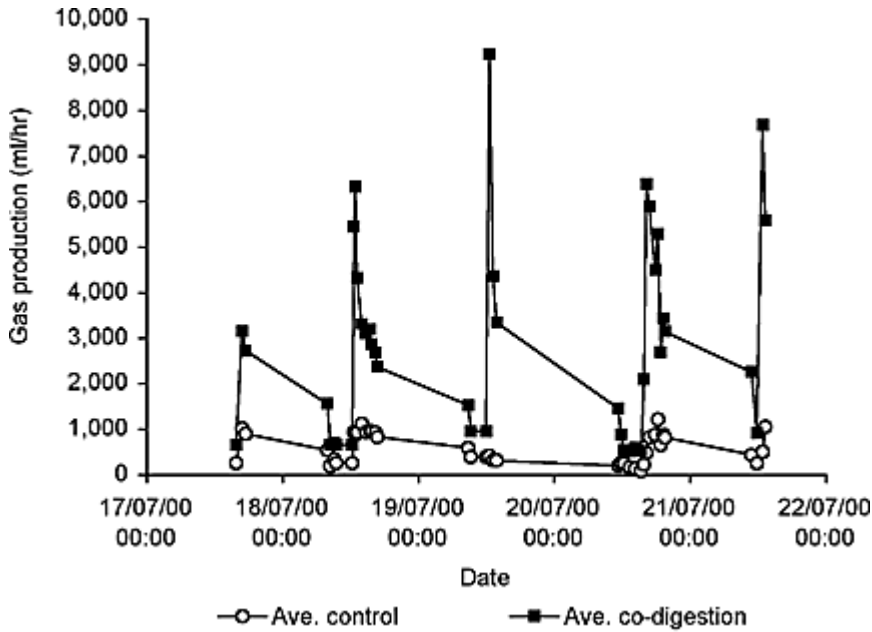


Figure 8. Daily gas production from control and co-digestion reactors

The greater gas production peaks from the co-digestion reactors were attributed to high volatile solids concentrations (average 83%) compared to primary sludge (average 72%) and more readily degradable organic matter. In other work, the metabolism of milk sugars was found to be very rapid. Mosey and Fernandes (1989) investigated shock loading and found using a digester fed on milk sugars, that VFA concentrations increased rapidly from 500-1000mg/L to peak concentrations of up to 2000mg/L following feeding.

Table 4 details the average and the range of methane recovery rates for control and co-digestion reactors. The data indicates greater methane recoveries for the co-digestion reactors than for the control reactors. These specific biogas and methane recoveries compare favourably with data presented in Table 4.

Parameter	Control	Co-digestion
Specific biogas production m ³ /kgVS added (averaged value)	0.315	0.538
Standard deviation	0.104	0.107
Specific methane production m ³ CH ₄ /kgVS added (averaged value)	0.204	0.310
Standard deviation	0.070	0.073

Table 3. Specific biogas and methane generation from control and co-digestion test reactors

Table 4. Full scale and experimental scale AD and co-digestion plants

Parameter	BTA process (Munich, Kelheim)	Dranco process	Valorga process	HRachi process	BWSC (Thersol)	DEMOS project	Warren Spring Laboratory Mesophilic trials	Warren Spring Laboratory Thermophilic trials
Reactor	Two stage & single stage	Dry fermentation	Dry fermentation	Slurry digestion – two phase with pretreatment	Single stage – wet thermophilic (manure)	Dry fermentation – single stage	Dry fermentation – single phase	Dry fermentation – single phase
Reactor volume (m ³)	11,000 tpa (Munich) 10,000 tpa (Kelheim)	56.5	503	1.5	90,000 tpa	26	0.01	0.01
Retention time (days)	14	12-21	15	8	15	20	18	19-23
Reactor temperature (°C)	37	55	35	60	55	35	35	55
Solids concentration (% DS)	8-10%	32%-35%	35%-40%	8%-16%	-	20%	33%-51%	33%-51%
OLR (kg VS/m ² d)	-	15-20	12-15	15	-	2.2-7.8	6.7-8.9	5.0-9.2
Biogas generation rate (m ³ biogas/tonne MSW added – dry wt)	-	164-168	144	-	26 (m ³ per manure wet wt)	150-200	-	-
Sp. methane generation (m ³ CH ₄ /tonne kg VS added)	-	0.22-0.29	0.20-0.27	0.31	-	-	0.098-0.12	0.123-0.223
Methane concentration (% vol)	60-65	55	60	68	55	50-52	51-56	51-54
VS destruction (% wt)	-	55	50	57	-	-	25-31	31-52

Source: INM (1990), De (1995), Damm et al. (1993), Nevay et al. (1993), Six & De Bener (1992)

Table 4. Full-scale and experimental-scale AD and co-digestion plants

6. CONCLUSION

Co-treatment of supermarket wastes and sewage sludge resulted in substantial increases in the levels of organic matter destruction and biogas generation. The main conclusions of the experimental co-digestion trials were:

1. Increasing organic loading rates from 2.0gVS/L.d to 6.0-6.5gVS/L.d resulted in up to 3 times greater biogas production with elevated levels of methane concentrations in the biogas. Further increases in organic loading rates to 7.6gVS/L.d inhibited methane production in a number of the co-digestion reactors and resulted in depressed pH values (pH 5.0), high VFA concentrations (16,500mg/l).
2. Average TS destruction rates throughout the project were 27.7% (standard deviation 13.3%) for the control reactors which is consistent with full-scale data. The performance of the co-digestion reactors produced a significantly higher TS destruction rate of 53.7% (standard deviation 12.0%). Average VS destruction rates throughout the project were 36.9% (standard deviation 12.9%) for the control reactors and 62.9% (standard deviation 12.4%) for the co-digestion reactors which is a substantial increase over control conditions.
3. The implications of these results for full-scale operation co-digestion are that blending supermarket produce wastes with sewage sludge at OLRs of up to 6.0-6.5gVS/L.d produced no detrimental effects on digester stability or exit sludge quality. The benefits to be realised at full-scale include significant increases in biogas generation and the increased potential for energy generation.

7. ACKNOWLEDGEMENTS

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