Working together for a world without waste

Summary Report

Anaerobic Digestion Doctor Technical Report: Plant A

This report summarises the findings of the WRAP appointed "Dr. AD" who investigated the operational processes of an AD site in England.

Project code: OIN002
Research date: 2012

ISBN: [Add reference]
Date: June 2013

WRAP's vision is a world without waste, where resources are used sustainably.

We work with businesses, individual and communities to help them reap the benefits of reducing waste, developing sustainable products and using resources in an efficient way.

Find out more at www.wrap.org.uk

Written by: Professor Charles Banks, University of Southampton

Front cover photography: [Add description or title of image.]

While we have tried to make sure this [plan] is accurate, we cannot accept responsibility or be held legally responsible for any loss or damage arising out of or in connection with this information being inaccurate, incomplete or misleading. This material is copyrighted. You can copy it free of charge as long as the material is accurate and not used in a misleading context. You must identify the source of the material and acknowledge our copyright. You must not use material to endorse or suggest we have endorsed a commercial product or service. For more details please see our terms and conditions on our website at www.wrap.org.uk

Contents

Table of Figures

List of Tables

Glossary

Abbreviations

RBP	Residual Biogas Potential
CHP	Combined Heat and Power
VS	Volatile Solids
TS	Total Solids
AD	Anaerobic Digestion
VFA	Volatile Fatty Acids
OLR	Organic Loading Rate

1. Introduction

This technical report covers the findings of Dr AD's investigation and analysis of Plant A's operational processes and performance.

The purpose of the Dr AD project was to engage with the operators of two commercial scale anaerobic digestion facilities treating mainly food waste to offer advice on ways their process could be improved and to facilitate the ability of the plant to gain PAS 110 accreditation. As an ancillary to this work the University of Southampton (UoS) carried out some basic analyses that would give further insight into digester performance and operational stability.

For confidentiality reasons the report shall refer to the AD facility as Plant A.

2. Report on Plant A

Prof Banks visited Plant A on 21 February 2012 where during the visit the plant history was discussed, availability of operational data was ascertained, and an agreement reached on provision of this to UoS, followed by a very informative tour of the plant and laboratories. Approximately 5 hours were spent on site, some of this in discussion of research by UoS that has led to the establishment of good operational practices for maintaining stability in food waste digesters. The topic of the RBP stability testing performed for the plant was discussed and a sheet showing the test results as presented by the testing agency was provided.

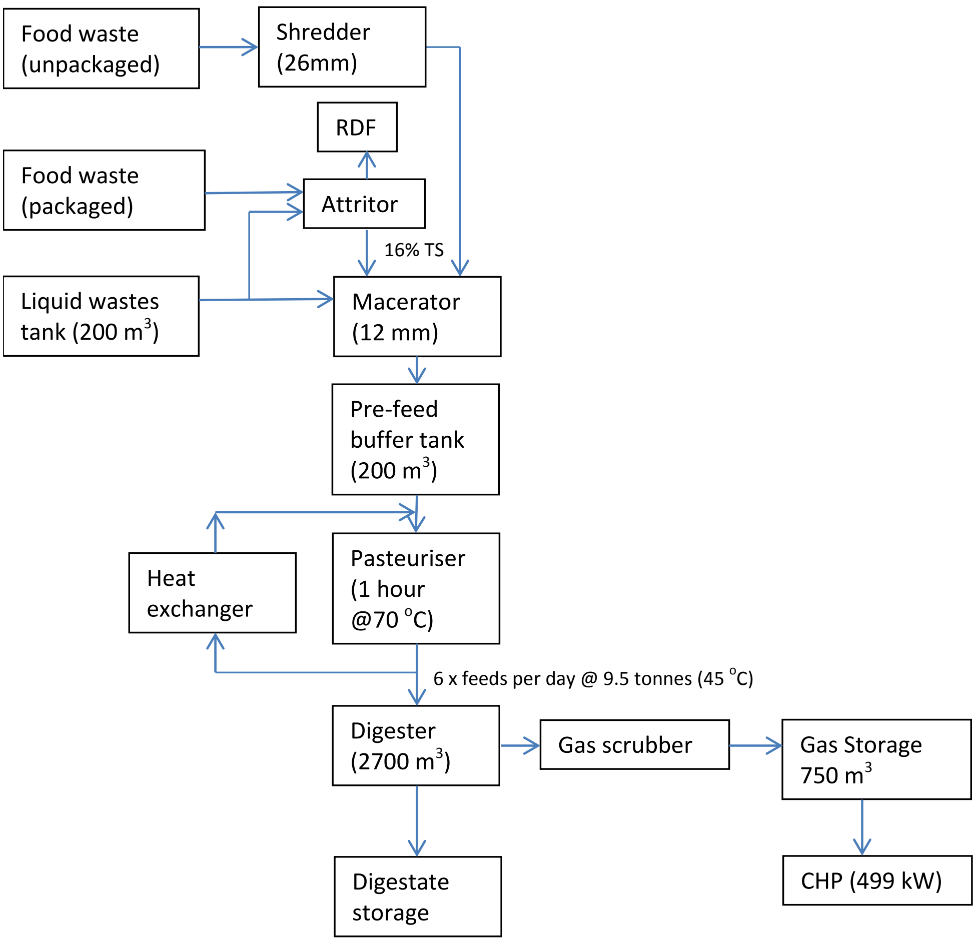


Figure 1 Process flow diagram for Plant A

Table F1. Process details for Plant A

Power output	499 kWe

Design tonnage	20-25000 tonnes/year
Design loading	3-3.5 kg VS/m^3-day
Input materials	Packaged commercial food waste (e.g. supermarket waste)
	Post-consumer domestic food waste
	Brewery liquid effluents, supermarket juices and soft drinks
Animal by-products compliance	Pre-pasteurisation 1 hour at 70 oC

Plant operational data were provided for the period from 15 November 2010 to 29 February 2012 and included the parameters shown in Table F2.

Table F2. Operational data for Plant A

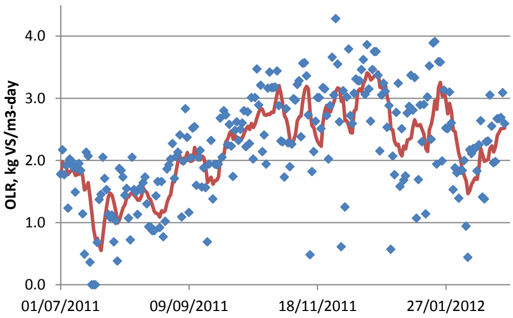
Gas composition (before and after desulphurisation - CH_4, H_2S, O_2, H_2S reduction)
Digester - daily feed in tonnes (food waste, manure), feed TS and VS, Organic loading, temperature, air supply
Digestion parameters - pH, digestate TS and VS, total VFA, alkalinity (including ratio of intermediate to partial alkalinity), ammonia
CHP - biogas composition, kWh output, operating hours

Data collection for some of these parameters was intermittent during the first few months of operation but in the last year has settled into a uniform pattern including regular laboratory analysis of samples as well as direct SCADA readings from continuously monitored probes and meters for gas composition and power generation. Further data on individual weighbridge inputs were also available but were not requested for the purposes of this report.

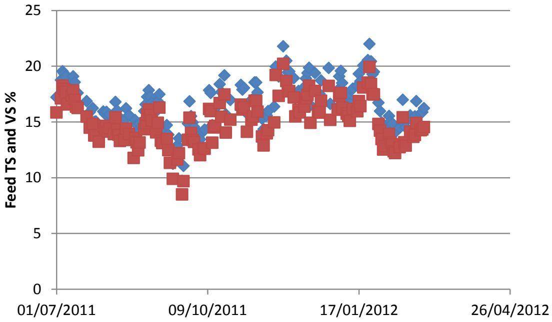
There is no direct measurement of biogas flow at the plant, and for the purposes of calculation this was estimated from the electricity generated, assuming a calorific value for methane of 36 MJ m^{-3} and electrical conversion efficiency for the CHP plant of 37%. All other results are as provided by the plant operators. The information was transcribed into a unified spreadsheet which will be made available to the plant operators but for the current report the results are presented below in graphical form.

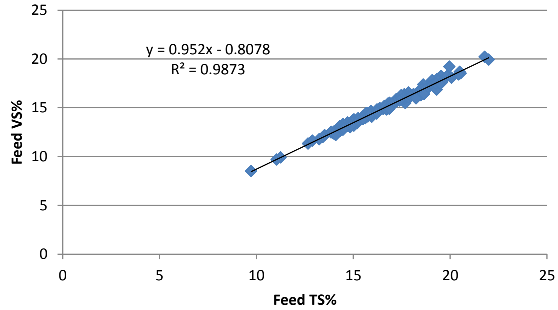
2.1. Organic loading

The organic load applied to the plant shows quite a large daily variation but there was a consistent upward trend for early July to end December 2011 reaching values of ~3 kg VS m^{-3} day^{-1}, after which the loading has been slightly reduced (Figure 2a). This appears to be associated with a reduction in the total and volatile solids content of the feed (Figure 2b), which may reflect the ratio of liquid to solid input materials (data not analysed). Figure 2c however shows that the ratio of TS to VS is very consistent with VS equal to around 95% of the TS content as is typical for food waste.



a) Organic loading rate: daily values and rolling weekly average





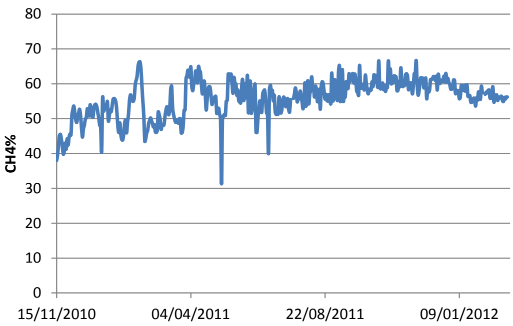
b) Feedstock TS and VS content against time c) Feedstock TS and VS relationship

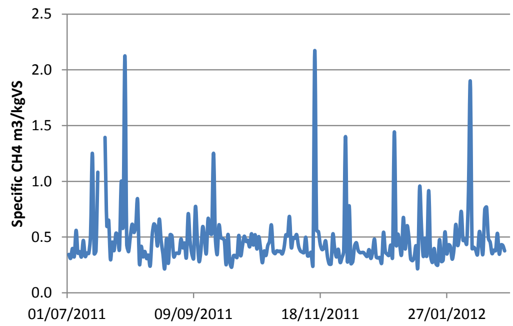
Figure 2 Feedstock solids characteristics and organic loading rate

2.2. Methane production

Values for the biogas composition were available from November 2010 and reflect the start-up process in which the methane content showed erratic peaks and troughs but was gradually increasing, reaching around 55% by July 2011 (Figure 3a). The methane concentration then rose to around 60%, probably corresponding to a reduction in accumulated volatile fatty acids (VFA) in the digester. It is not known what interventions if any were made at this period to cause this change.

The specific methane production of the plant, calculated from the electricity production as described above, averaged 0.474 m^3 CH_4 kg^{-1} VS added. This is slightly higher than typically observed for digesters treating only source segregated domestic food waste and may reflect the nature and composition of the commercial food waste inputs; or may be due to incorrect estimation of the CHP plant efficiency. Figure 3b shows the specific methane yield against time calculated on a daily basis: the large spikes are due to occasional days of low feed inputs with gas production continuing as a result of the previous days' feed.



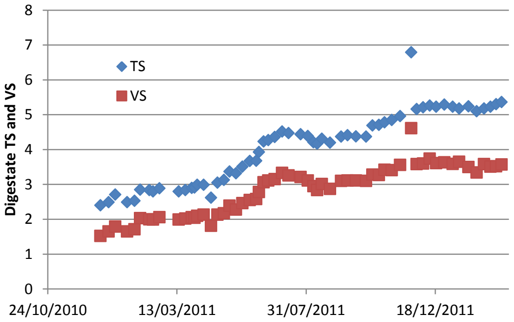


a) Biogas methane content against time b) Specific methane yield against time

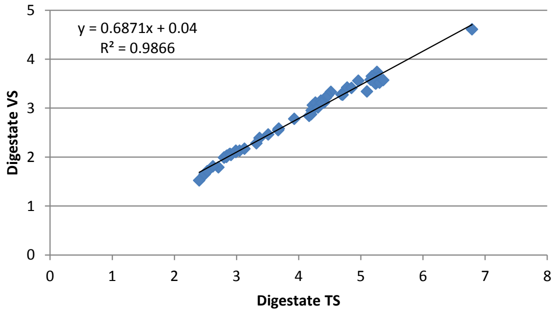
Figure 3 Biogas methane content and feedstock specific methane yield

2.3. Digestate TS and VS

Figure 4 shows the digestate TS and VS content, it can be seen that the ratio of VS has fallen to about 69% of TS content compared with the 95% in the incoming feed. Since November 2011 the digestate VS content has stabilised at around 3.6% compared to the feedstock average of 15.7% over the same period, giving an approximate VS conversion rate of 77%. These parameters indicate that the plant is performing well in the conversion of the input material to biogas.



b) Digestate TS and VS content against time

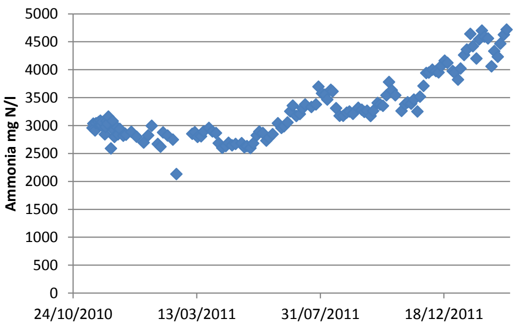


c) Digestate TS and VS relationship

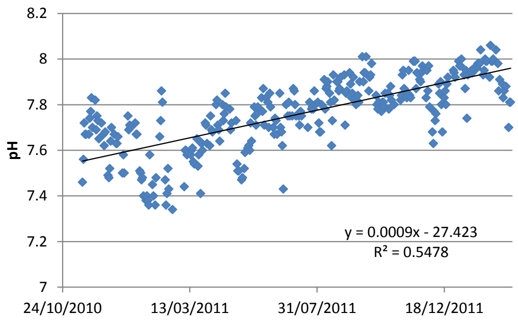
Figure 4 Digestate solids characteristics

2.4. Digestion stability parameters

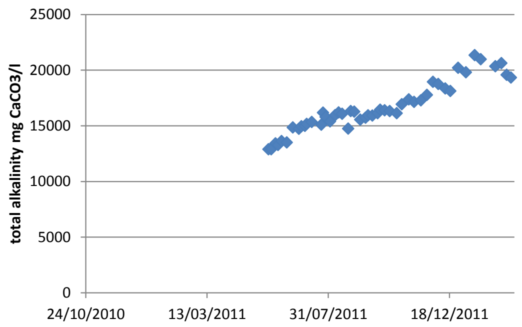
One of the major concerns in the digestion of food waste as a sole substrate is the unfavourable carbon to nitrogen ratio as a result of the high protein content in the feedstock. Figure 5 shows the main digestion stability parameters monitored at the plant. The results indicate that there has been a substantial increase in ammonia concentration from November 2011 (Figure 5a). This is reflected in the increasing pH and alkalinity, which are now over 8 and 20 g $CaCO_3$ l^{-1} respectively (Figure 5b and c). In themselves these parameters are not a cause for concern as stable operation can be achieved in these conditions. Based on the plant's own data, however, there may be signs of incipient instability. The ratios of intermediate alkalinity to partial alkalinity (IA/PA) and of VFA to total alkalinity (VFA/TA) are both rising fairly sharply (Figure 5d): these are very sensitive indicators of the onset of unfavourable conditions. VFA concentrations, which reached values over 8000 mg l^{-1} during the start-up period then stabilised in the region of 3500 mg l^{-1}, have started to increase (Figure 5e); and there is a corresponding small drop in biogas methane concentration (Figure 3a).



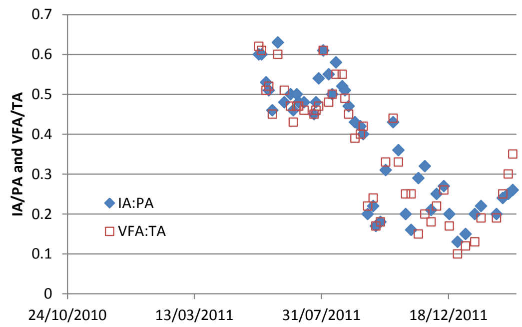
a) Ammonia N



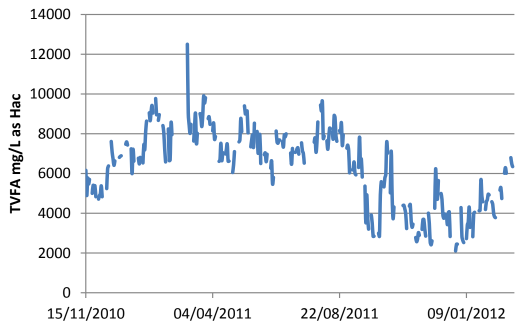
b) pH



c) Total alkalinity



d) IA/PA and VFA/TA ratio



e) Total VFA concentration

Figure 5 Digestion stability parameters

The analysis results of a sample taken by UoS on 21 February 2012 are shown in Table 1. These showed a lower VFA concentration than that measured in the plant's laboratory, although this may in part be due to differences in the analytical techniques used. In the UoS sample the majority of the VFA was in the form of acetic acid, but with propionic acid making up more than 10% of the total. Some of the other parameters measured are similar to, or lower than, the values obtained in the plant laboratory, but the IA/PA ratio is higher and more importantly the plant results are able to capture gradual trends.

Table 1 Analytical results for digestate sample taken on 21 February 2012

Ammonia	weight g	V ml	mg N/l						
	1.32	1.83	4665						
	2.16	2.99	4688						
		average	4677						
		stdev %	0.35						
Alkalinity	Weight g	V 5.7 ml	V 4.3 ml	V 4 ml	TA	PA	IA	IA/PA	
	2.67	3.48	1.63	0.22	24953	16292	7631		
	1.19	1.5	0.75	0.17	25420	15756	7878		
				average	25187	16024	7755	0.48	
				stdev %	1.31	2.36	2.25		
TS and VS	W1 (g)	W2 (g)	W3 (g)	W4 (g)	TS %	VS %	TS g/kg	VS g/kg	%VS of TS
	45.357	71.175	46.707	45.821	5.23	3.43	52.29	34.32	
	41.754	56.639	42.518	42.016	5.13	3.37	51.33	33.73	
	44.334	65.847	45.468	44.715	5.27	3.50	52.71	35.00	
				average	5.21	3.43	52.11	34.35	65.9%
				stdev %	1.36	1.86	1.36	1.86	
VFA	Acetic	Propionic	Iso-Butyric	n-Butyric	Iso-Valeric	Valeric	Hexanoic	Heptanoic	Total
	3283	387	50	9	60	0	0	0	3789

2.5. Trace element status

Previous work has shown that as ammonia concentrations rise about 3.5 - 4.0 g N l^{-1} it is critical to maintain adequate supplies of essential trace elements. The plant operators reported that they used a specific additive at a does rate of 150 ml per 50 tonnes of feedstock addition. The elemental composition and concentration of this additive is not known and the only information provided on the product Materials Safety Data Sheet is that it contains nickel and cobalt complexed with a named chelating agent and other trace elements. The digestate sample taken on 21 February was acid extracted at UoS and the extract was analysed for trace element concentrations by Severn Trent Laboratories. The results are shown in Table 2. It should be emphasised that these values are based on a spot sample and do not provide any information about the longer term trace element status of the digester. This is especially the case when there have been changes in trace element supplementation strategy, as the current values may only be a snapshot taken during a process of washout or accumulation.

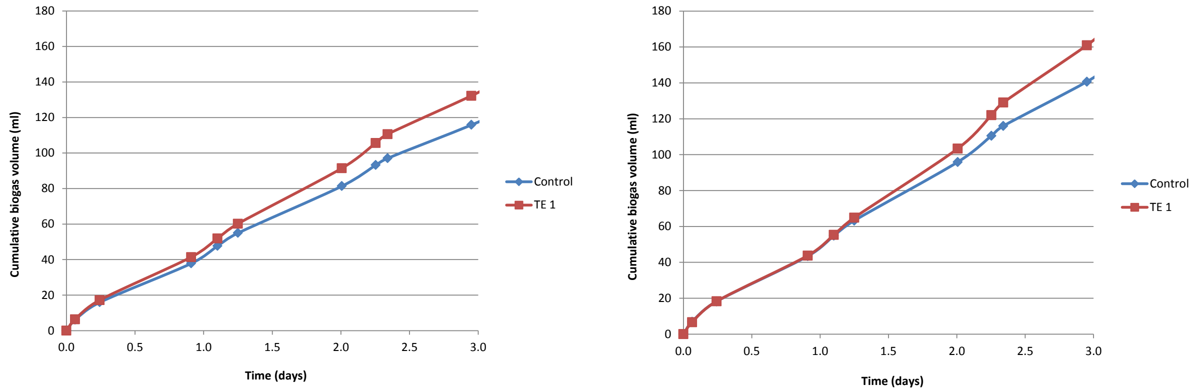
Table 2 Trace element concentrations in Plant A digestate

	Co	Cu	Fe	Mn	Mo	Ni	Zn	Se
mg kg^{-1} wet weight	0.10	1.90	76.15	7.89	0.15	0.30	7.10	0.08
mg kg^{-1} TS	1.88	36.54	1461	151.4	2.89	5.77	136.3	1.52

Based on UoS experience with digestion of source segregated domestic food waste, for stable operation at OLR of up to 5 kg VS m^{-3} day^{-1} and with a plant achieving ~80% VS destruction the required steady state concentrations of Cobalt and Selenium in the digestate are around 4.4 and 3.2 mg kg^{-1} TS respectively. Nickel has not been found to be deficient in food waste, and plants appear to operate well with a concentration of around 3.5 mg kg^{-1} TS in the digestate. At lower OLR smaller concentrations of the above trace elements may be sufficient as there is a lower requirement for enzyme production. On the basis of this the concentration of Plant A's digestate appear to be limited in terms of selenium and cobalt. This conclusion is also based on the assumption that the metals are available and not bound to the chelating agent so strongly that they cannot be utilised by the microbial consortium.

To further assess whether trace elements might be deficient an additional test was carried out based on the procedure recommended by Speece (1996)[1], in which samples of digestate are placed in serum bottles and supplemented with a trace element mixture. The resulting gas production, determined from pressure increase, was measured over a 72-hour period and the test results are shown in Figure 6. An increase of 14% in gas production in the test samples compared to unsupplemented controls was observed, indicating possible trace element deficiency. A modification of the test was also undertaken in which the digestate was given a supplement of acetate to ensure that a readily degradable methanogenic substrate was present; this test also gave a 14% difference between supplemented and unsupplemented samples. The test was carried out in duplicate only due to the limited amount of digestate available, and it was therefore not possible to express the results in terms of standard deviations, as recommended by Speece (1996), but the results are indicative of trace element deficiency.

[1] *Speece, R.E. (1996) Anaerobic Biotechnology for Industrial Wastewaters Archae Press, Nashville, Tennessee.*



a) No acetate addition b) 3000 mg HAc /l addition

Figure 6 Trace element supplementation test

2.6. RBP test results

A Residual Biogas Potential (RBP) test was carried out on digestate taken directly from the digester outlet. The test was carried out in accordance with the PAS110 protocol (Walker et al., 2010), and the results are reported according to the specified format.

1. A plot of digestate RBP (RBPD), based on the average of the triplicate values for each day the biogas was measured (See Figure 7).

2. On the same graph as for item 1, a plot of the reference sample RBP (cellulose), based on the average of the triplicate values for each day the biogas was measured (See Figure 7).

3. On the same graph as for item 1, a plot of the inoculum RBP, based on the average of the triplicate values for each day the biogas was measured (See Figure 7).

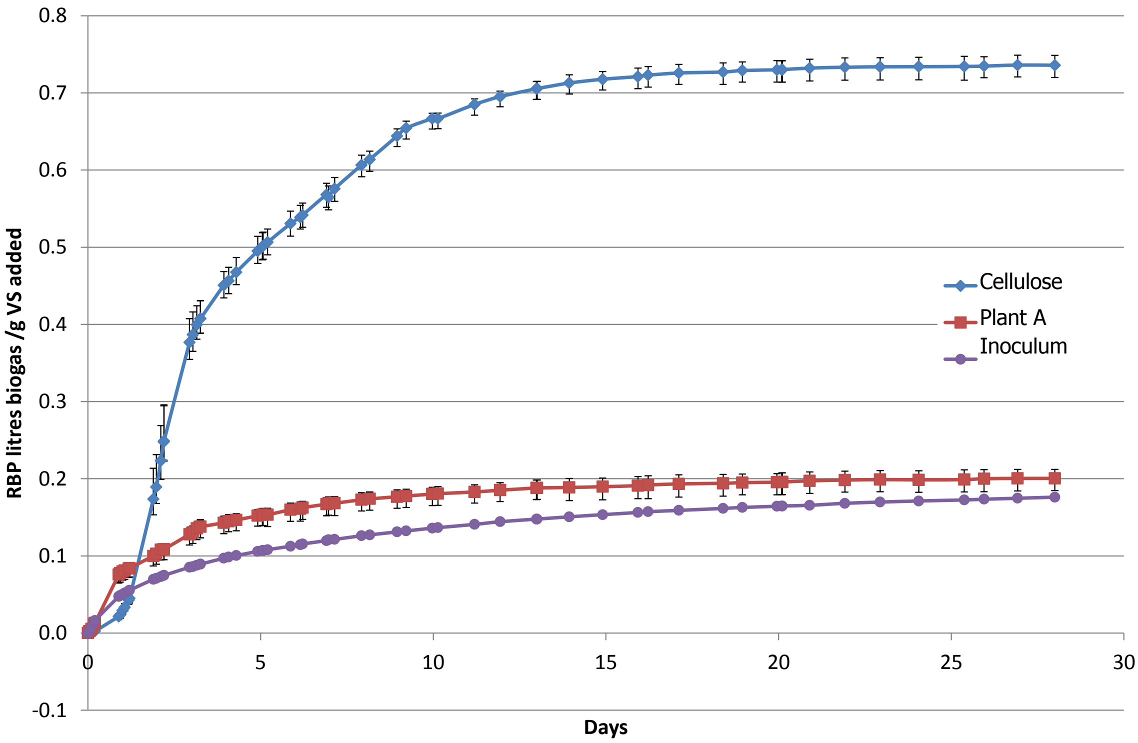


Figure 7 Plot of digestate, inoculum, and cellulose RBPs based on the average of the triplicate values for each day the biogas was measured. (Error bars show range of triplicate measurements).

4. The triplicate TS and VS values of each material (digestate, reference and inoculum before use in the RBP tests), and the calculated averages of each material's TS and VS values (See Table 3).

Table 3 Total and volatile solids contents for digestate, control sample and inoculum

Parameter	Unit	Cellulose			Plant A digestate			Inoculum		
TS	%WW	96.3	96.9	96.1	5.30	5.21	5.25	3.83	3.82	3.84
VS	%WW	96.4	96.9	96.1	3.51	3.43	3.48	2.60	2.60	2.62
VS	%TS	100.0	100.0	100.0	66.3	65.8	66.3	68.1	68.1	68.2
average TS	g TS kg^{-1} WW	96.5			5.25			3.83		
average VS	%WW	96.5			3.47			2.61		
average VS	g VS kg^{-1} WW	964.66			34.73			26.08		

5. The triplicate values of the 28-day inoculum control RBP, and the calculated average of those values (See Table 4).

6. The triplicate values of the 28-day reference sample RBP (cellulose), and the calculated average of those values (See Table 4).

7. The triplicate values of the 28-day digestate sample RBP, and the calculated average of those values (See Table 4).

Table 4 RBP results

Digestate	**Value**		
VS digestate (g / kg)	34.73		
weight of digestate added (g)	55.33	55.30	55.33
weight of inoculum added (g)	345	345	345
digestate test gas production (l)	1.983	1.969	1.930
average inoculum contribution (l)	1.585	1.585	1.585
RBP test sample (l / g VS)	0.207	0.200	0.180
Average RBP test sample (l / gVS)	0.196		
Reference sample (cellulose)	**Value**		
VS reference (g / kg)	964.66		
weight of reference material added (g)	1.551	1.550	1.545
weight of inoculum added (g)	398	398	398
reference test gas production (l)	2.938	2.894	2.919
average inoculum contribution (l)	1.829	1.829	1.829
RBP reference sample (l / g VS)	0.741	0.713	0.732
average RBP reference sample (l / gVS)	0.729		
Inoculum	**Value**		
VS inoculum (g / kg)	26.08		
weight of inoculum added (g)	400	400	400
inoculum test gas production (l)	1.845	1.841	1.828
RBP of inoculum (l / g VS)	0.177	0.176	0.175
average RBP inoculum (l / gVS)	1.838		
specific inoculum gas production (l / g)	0.00461	0.00460	0.00457
average inoculum gas production (l / g)	0.00459		
Ratio checks			

Inoculum/substrate on a VS basis for the digestate RBP tests (should be around 4 for the digestate RBP tests)*	4.68	4.68	4.68
Inoculum/substrate on a VS basis for the reference RBP tests (should be around 6 for the reference RBP tests)*	6.94	6.94	6.97

* Slightly lower values achieved in current test due to slightly higher than expected inoculum VS content, which was only measured after setting up the test to minimise delay and keep digestate storage period within test limit value. No adverse effect on results - see below.

2.7. Inoculum test quality control

1. The inoculum control should produce a measurable volume of biogas over the 28 day period. If no biogas production is observed the inoculum is unsuitable.

Inoculum biogas production during the test was approximately 1.8 litres corresponding to an RBP of 0.176 l biogas g^{-1} VS added.

2. The plots of the inoculum RBP (one plot line of RPBI results for each of the sample triplicates) should be smooth with no obvious spikes or inconsistencies that suggest faulty equipment (temperature, leaks etc.) or incorrect calculation methods.

All of the inoculum RBP values were consistent and smooth, with no obvious spikes or inconsistencies, as can be seen from the values and error bars in Figure 8.

The test was thus valid from the viewpoint of inoculum quality control indicators.

2.8. Reference material test quality control

1. The reference material RBP is allowed to be negative only during the first 5 days of the test. If the reference material RBP is negative beyond the first 5 days of the test the inoculum is unsuitable.

The reference material RBP was not negative at any point in the test, as can be seen from the values and error bars in Figure 8.

2. The 28-day RBP of the reference material should exceed 0.5 litre of biogas per gram volatile solids.

The 28-day RBP of the reference material was 0.73 l biogas g^{-1} VS added, and was therefore satisfactory.

3. The plots of the reference RBP (one plot line of RBPR results for each of the sample triplicates) should be smooth with no obvious spikes or inconsistencies that suggest faulty equipment (temperature, leaks etc.) or incorrect calculation methods.

All of the reference material RBP values were consistent and smooth, with no obvious spikes or inconsistencies, as can be seen from the values and error bars in Figure 7.

The test was thus valid from the viewpoint of reference material quality control indicators.

2.9. Digestate test quality control

1. The digestate RBP is allowed to be negative only during the first 5 days of the test. If the digestate RBP is negative beyond the first 5 days of the test, the test is invalid as the inoculum is being inhibited.

The RBP of one sample of digestate was fractionally below zero (-0.001 l biogas g^{-1} VS) for approximately 2.5 hours on the first day (from 0.04 - 0.1 days). This negative value is too small to be seen from the values and error bars in Figure 7.

2. The plots of the digestate RBP (one plot line of RBPD results for each of the sample triplicates) should be smooth with no obvious spikes or inconsistencies that suggest faulty equipment (temperature, leaks etc.) or incorrect calculation methods.

All of the digestate RBP values were consistent and smooth, with no obvious spikes or inconsistencies as can be seen from the values and error bars in Figure 7.

The test was thus valid from the viewpoint of digestate quality control indicators, and the whole test results can therefore be considered valid. As the VFA concentration in the digestate samples was < 4000 mg l^{-1} and the RBP value of 0.196 litres g^{-1} VS was < 0.25 litres g^{-1} VS the digestate samples would have passed a PAS110 stability test.

3. Conclusion

After implementing a series of recommendations based on the findings presented in this technical report, Site A was able to increase its biogas output by optimising which trace elements were used and the location they were added to the digester. Furthermore as the stability of the digester improved Site A was able to achieve accreditation to the Bio Fertiliser Certification Scheme (PAS 110).

www.wrap.org.uk/relevant link

Waste & Resources Action Programme

The Old Academy
21 Horse Fair
Banbury, Oxon
OX16 0AH

Tel: 01295 819 900
Fax: 01295 819 911
E-mail: info@wrap.org.uk

Helpline freephone
0808 100 2040

Printed on xx% recycled content paper

recycle