Anaerobic digestion of food waste
technical issues and solutions

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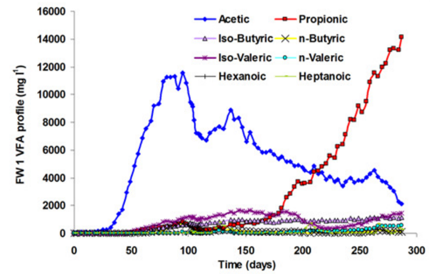
A short history

2003 – First pilot scale study, mesophilic and thermophilic

2006 – 2009 Laboratory studies confirming earlier observations

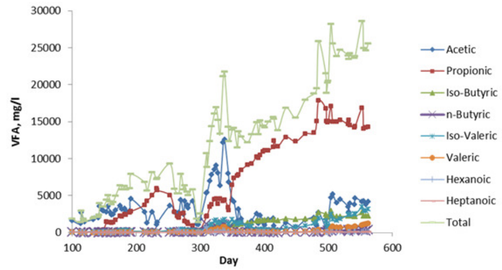
VFA of 27,400 mg l^{-1} after 35 weeks of operation

Ammonia concentration around 5200 mg l^{-1} (before dilution)



After 120 days VFA began to accumulate

Changing VFA profile from acetic to predominantly propionic acid



2006 – 2010 commissioning of first demonstration plant, and problems at a large scale

SEVENTH FRAMEWORK PROGRAMME

VALORGAS

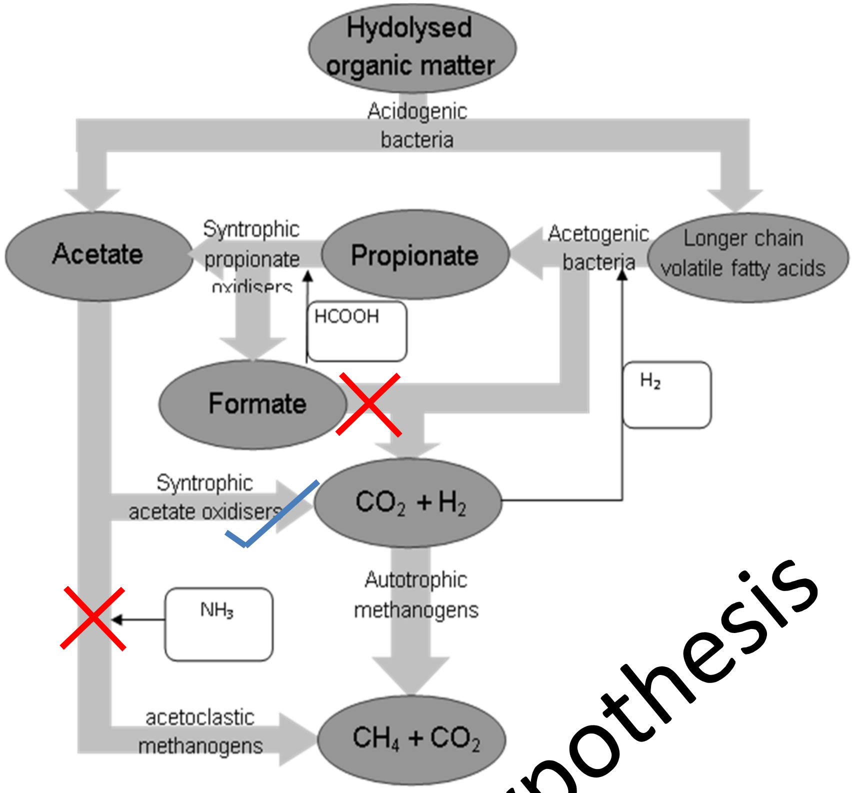
Facts to hypothesis

Accumulation of VFA after extended period of time	Something accumulating? Something depleted?
Acetic acid peak replaced by propionic acid peak	Loss of acetoclastic methanogens could lead to acetic acid peak
Accumulation of ammonia	Ammonia known to be toxic to acetoclastic methanogens
Can carbon flow to methane in the absence of acetoclastic methanogens?	Could have methane production from hydrogen and carbon dioxide (hydrogenotrophic route)
Why does propionic acid accumulate?	Uneven carbon chain length – breaks down to acetic and formic acids
What is the significance of formic acid?	Accumulation of formic acid will stop further breakdown of propionic acid
Formic acid can only be used by hydrogenotrophic methanogens	Is there a special enzyme system needed?
Selenium and Tungsten possibly essential trace elements for formate dehydrogenase enzyme system	Are these commonly added in trace element formulations? What is the concentration in food waste?

FACTS

- Ammonia toxic to acetoclastic methanogens less toxic to hydrogenotrophic methanogens
- Propionic acid accumulation is due to insufficient capacity of hydrogenotrophic methanogens to synthesis formate dehydrogenase enzyme
- Requirement for Se as part of this enzyme complex

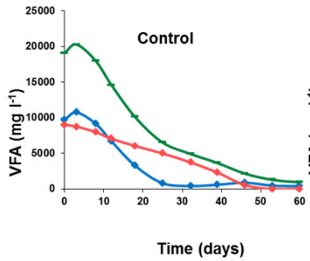
Conclusions drawn

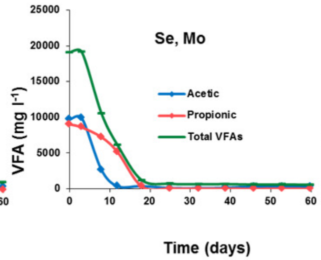


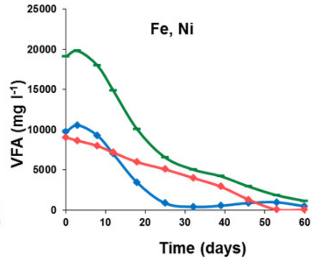
Hypothesis

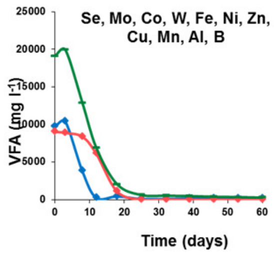
Batch screening tests

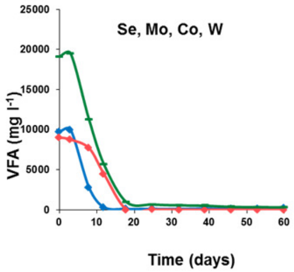
Run	Pattern	Co	Ni	Mo	Se	Fe	W	Zn	Cu	Mn	Al	B
1	−−−−−−−−−−−	-	-	-	-	-	-	-	-	-	-	-
2	−−−+++−−−−−	-	-	-	Se	Fe	W	-	-	-	-	-
3	−−+−++−−−−−	-	-	Mo	-	Fe	W	-	-	-	-	-
4	−−++−−−−−−−	-	-	Mo	Se	-	-	-	-	-	-	-
5	−+−−+−−−−−−	-	Ni	-	-	Fe	-	-	-	-	-	-
6	−+−+−+−−−−−	-	Ni	-	Se	-	W	-	-	-	-	-
7	−++−−+−−−−−	-	Ni	Mo	-	-	W	-	-	-	-	-
8	−++++−−−−−−	-	Ni	Mo	Se	Fe	-	-	-	-	-	-
9	+−−−−+−−−−−	Co	-	-	-	-	W	-	-	-	-	-
10	+−−++−−−−−−	Co	-	-	Se	Fe	-	-	-	-	-	-
11	+−+−+−−−−−−	Co	-	Mo	-	Fe	-	-	-	-	-	-
12	+−++−+−−−−−	Co	-	Mo	Se	-	W	-	-	-	-	-
13	++−−++−−−−−	Co	Ni	-	-	Fe	W	-	-	-	-	-
14	++−+−−−−−−−	Co	Ni	-	Se	-	-	-	-	-	-	-
15	+++−−−−−−−−	Co	Ni	Mo	-	-	-	-	-	-	-	-
16	++++++−−−−−	Co	Ni	Mo	Se	Fe	W	-	-	-	-	-
17	+++++++−−−−	Co	Ni	Mo	Se	Fe	W	Zn	-	-	-	-
18	+++++++++−−	Co	Ni	Mo	Se	Fe	W	Zn	Cu	Mn	-	-
19	+++++++++++	Co	Ni	Mo	Se	Fe	W	Zn	Cu	Mn	Al	B

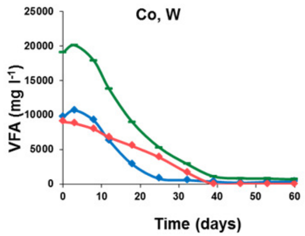










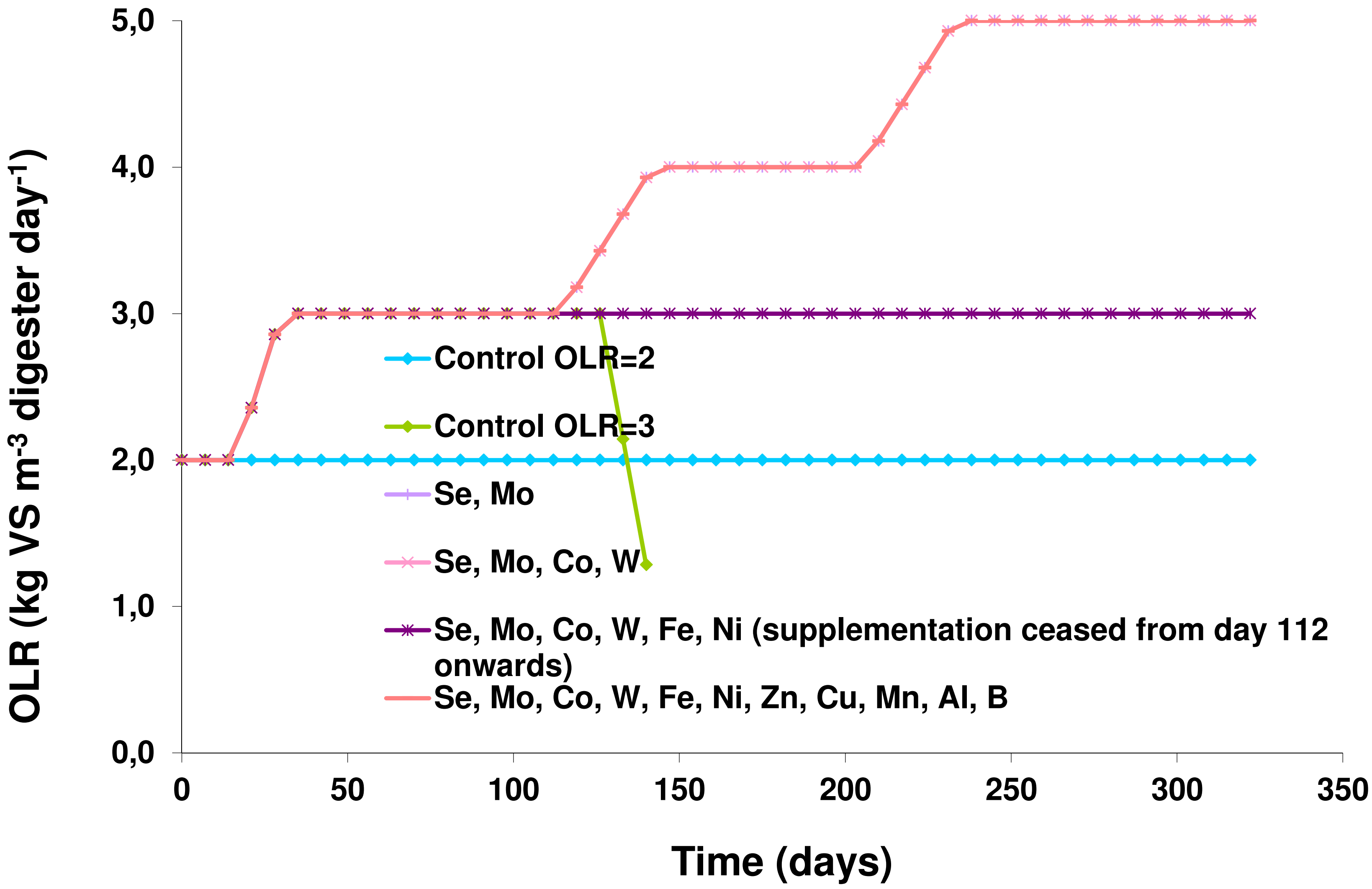


Semi-continuous anaerobic digestion trials

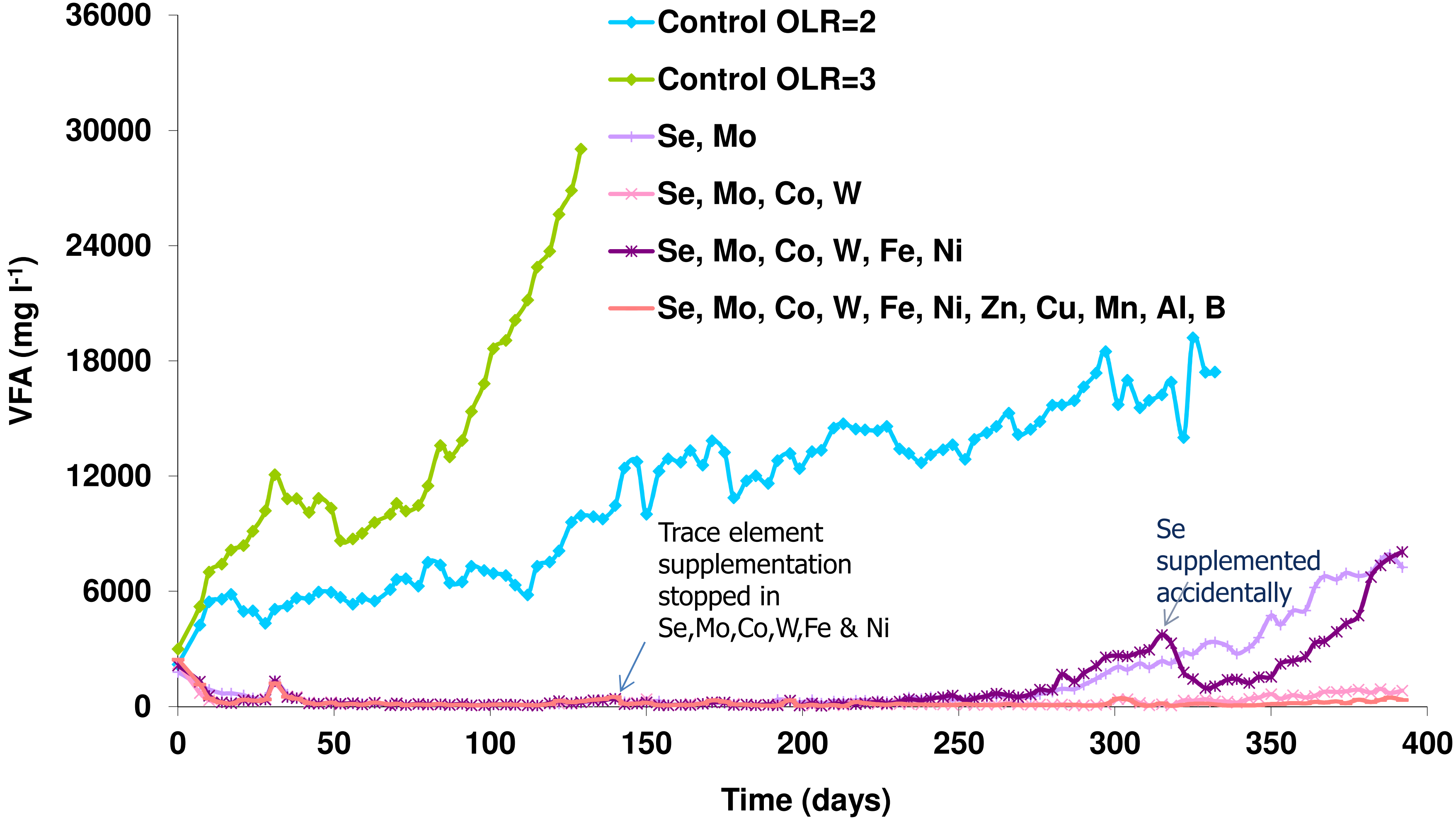
Supplemented with:

- Trace element combinations
- Single trace element

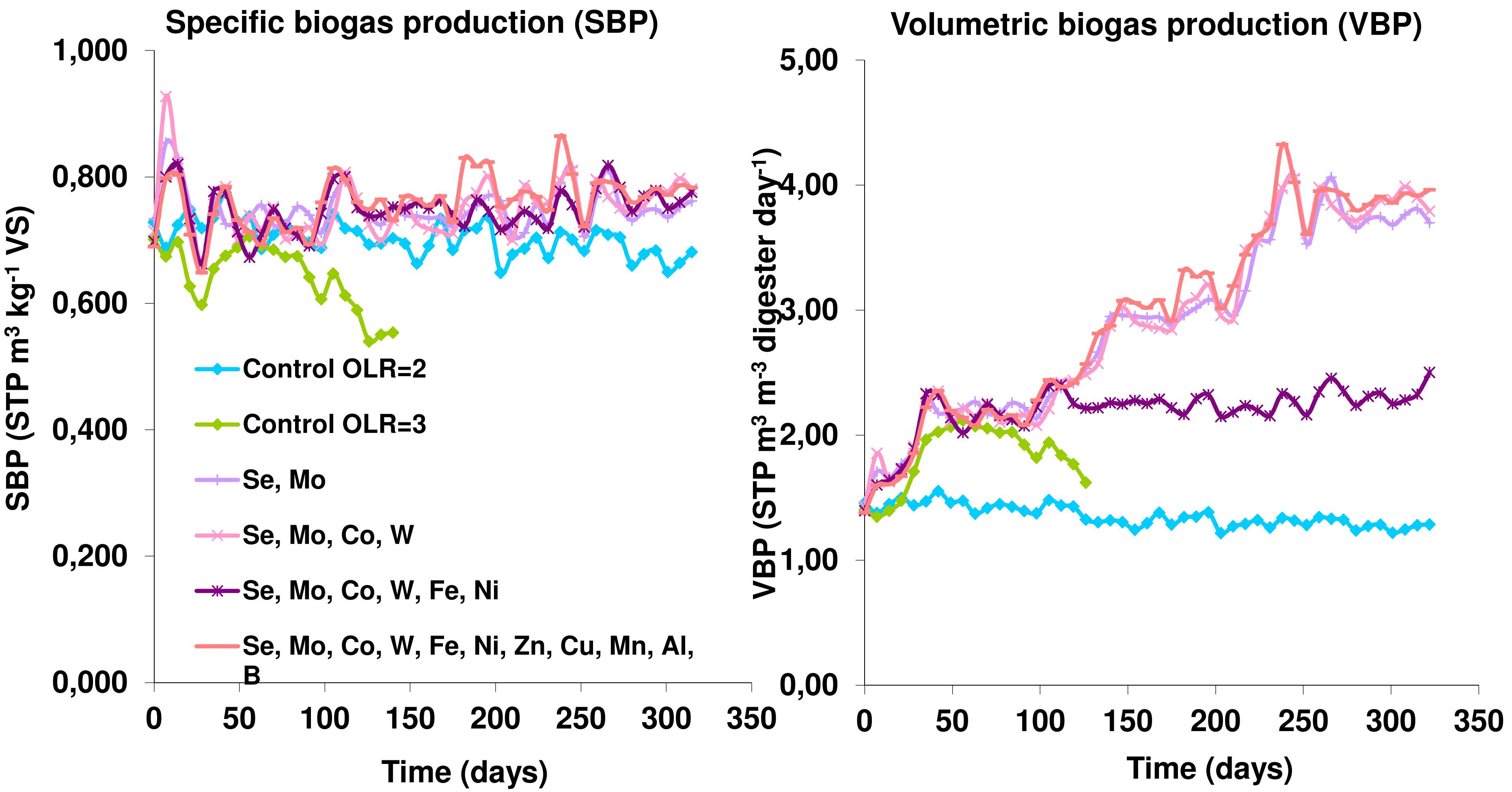
Organic loading rate (OLR)



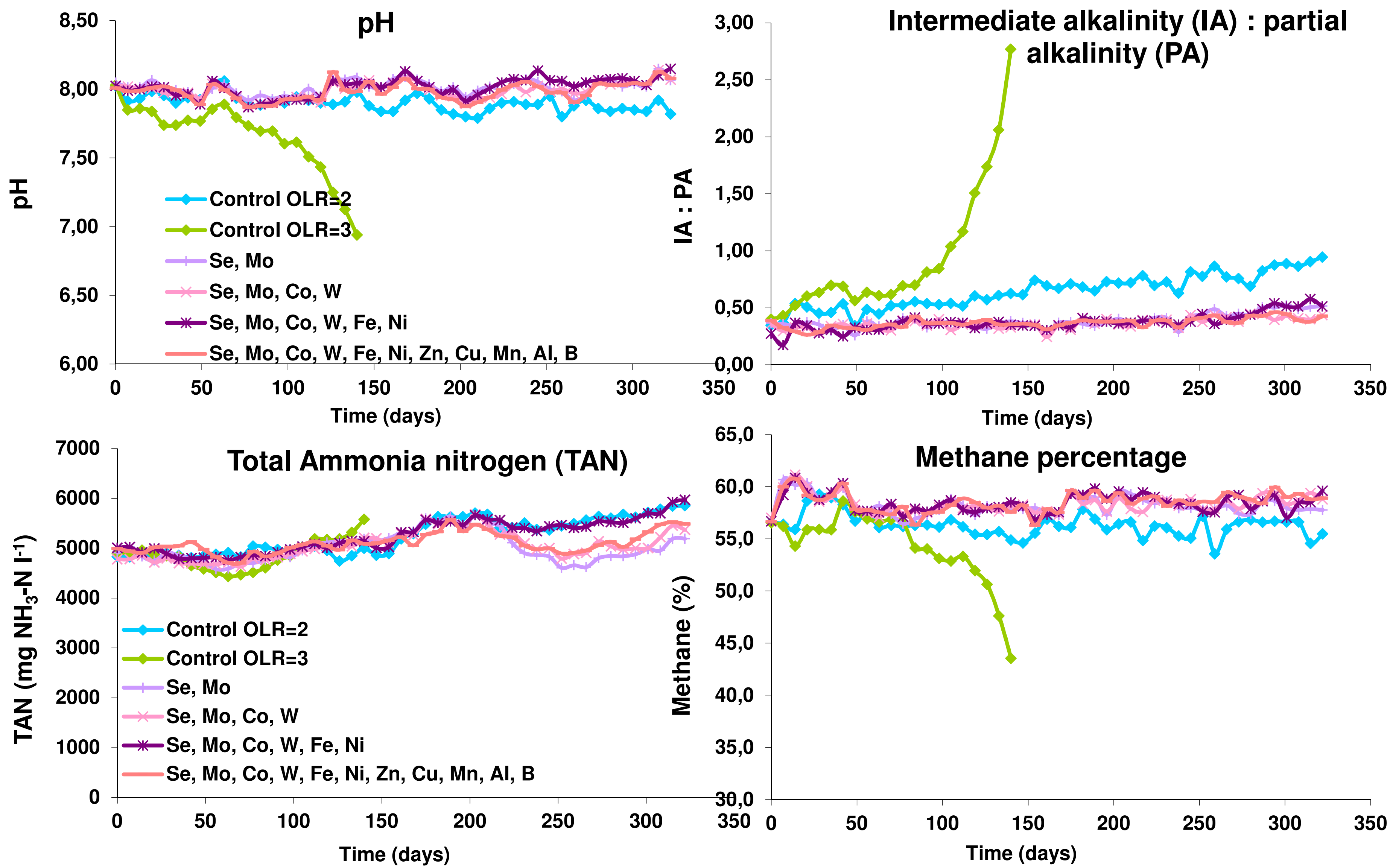
Volatile fatty acid profiles



Digestion efficiency



Other digestion parameters



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Selected publications

More information on
www.bioenergy.soton.ac.uk
www.valorgas.soton.ac.uk

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

Charles J. Banks, Michael Chesshire and Anne Stringfellow

ABSTRACT

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

Key words | food waste, kitchen waste, mesophilic, thermophilic, volatile fatty acids

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Trace element requirements for stable food waste digestion at elevated ammonia concentrations

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ABSTRACT

The work investigated why anaerobic digesters treating food waste and operating at high ammonia concentrations suffer from propionic acid accumulation which may result in process failure. The results showed deficiency of selenium, essential for both propionate oxidation and syntrophic hydrogenotrophic methanogenesis, leads to this while supplementation allows operation at substantially higher organic loading rates (OLR). At high loadings cobalt also becomes limiting, due to its role either in acetate oxidation in a reverse Wood-Ljungdahl or in hydrogenotrophic methanogenesis. Population structure analysis using fluorescent in situ hybridization showed only hydrogenotrophic methanogens. Critical Se and Co concentrations were established as 0.16 and 0.22 mg kg^{-1} fresh matter feed at moderate loading. At this dosage the OLR could be raised to 5 g VS l^{-1} day^{-1} giving specific and volumetric biogas productions of 0.75 m^3 kg^{-1} VS_{added} and 3.75 STP m^3 m^{-3} day^{-1}, representing a significant increase in process performance and operational stability.

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Anaerobic digestion of two biodegradable municipal waste streams

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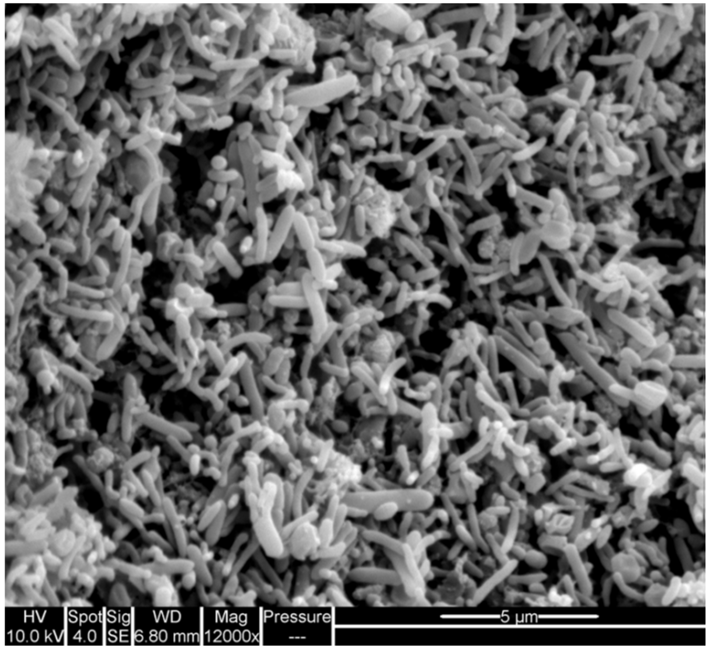
ABSTRACT

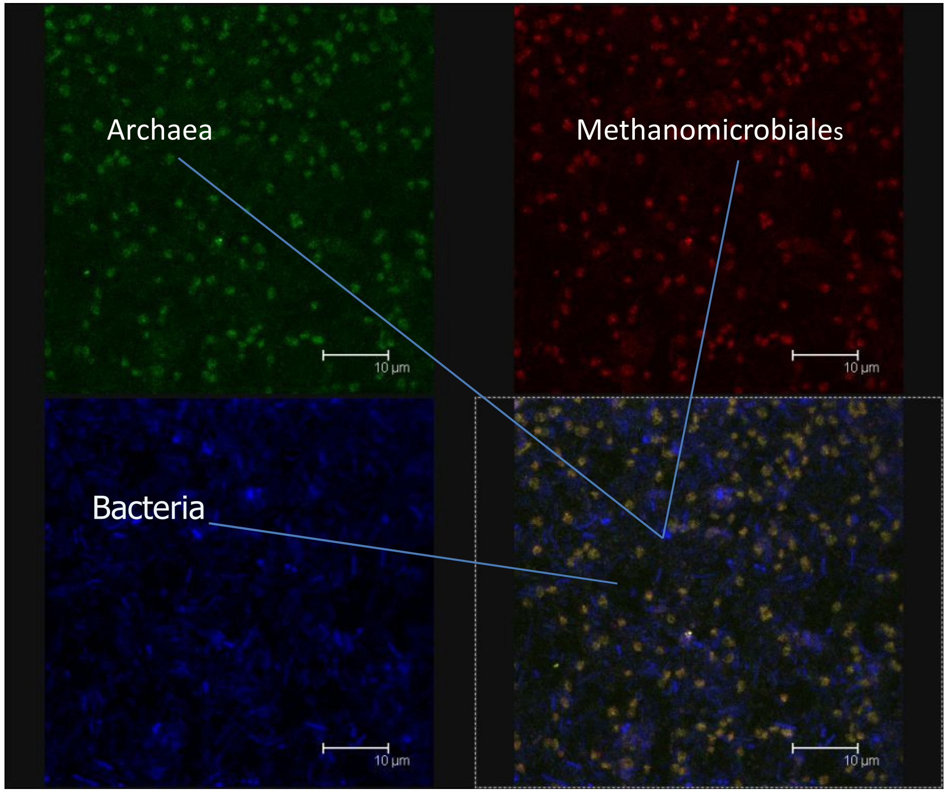
Landfill avoidance for organic wastes is now a high priority worldwide. Two fractions of the municipal waste stream were considered with respect to their potential for diversion through controlled anaerobic digestion. The physical and chemical properties of source segregated domestic food waste (ss-FW) and of the mechanically-recovered organic fraction of municipal solid waste (mr-OFMSW) were analysed, and their methane yields determined in both batch and semi-continuous digestion. Methane potentials were compared with predicted values based on biochemical composition, elemental analysis and carbon mass balance, and the differences explained by compositional analysis of feedstocks and digestates. The ss-FW had a higher percentage biodegradability and higher energy potential on a dry weight basis due to the high proportion of proteins and fats in this waste, although the energy potential of the mr-OFMSW was slightly higher on a wet weight (WW) basis. The mr-OFMSW showed very stable digestion characteristics, whereas the ss-FW had a high digestate ammoniacal-N concentration and volatile fatty acid accumulation leading to some process instability. Digestates from semi-continuous trials with mr-OFMSW had high concentrations of potentially toxic elements (PTE) and a lower nutrient content than ss-FW digestate, making the former unsuitable for application to land used in food production.

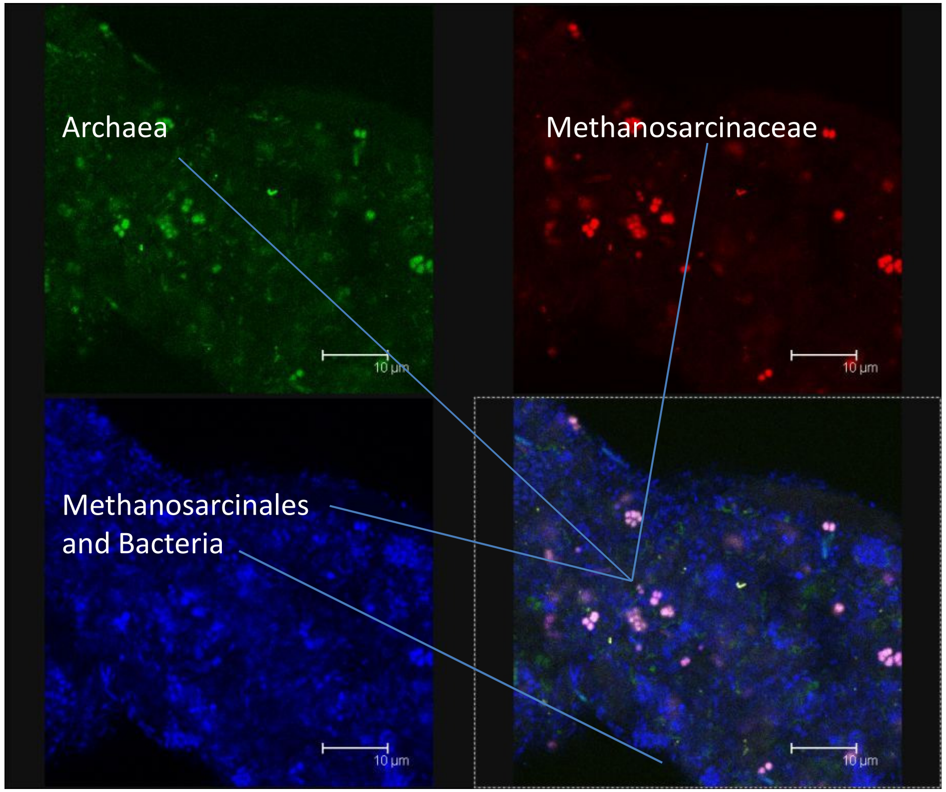
Microbial community structure analysis



Methanogen	Carbon source
Order I. Methanobacteriales	CO_2 / H_2 and formate
Order II. Methanococcales	CO_2 / H_2 and formate
Order III. Methanomicrobiales	CO_2 / H_2 and formate
Order IV. Methanosarcinales	
Family I. Methanosaetaceae	Acetate
Family II. Methanosarcinaceae	Acetate Methylated one-carbon compounds CO_2 / H_2 and formate

FISH images

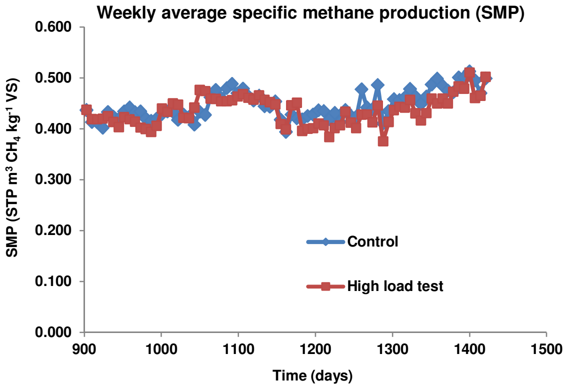


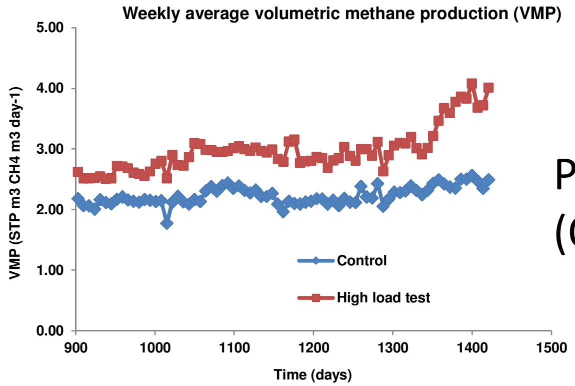


Methanomicrobiales **(food waste digestion)** ***Methanosarcinaceae*** **(vegetable waste digestion)**

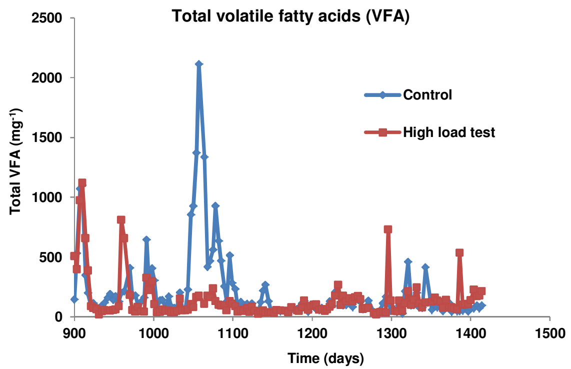
Probe name	Target group	Probe sequence (5'-3')	Fluorescent dye	Fluorescent colour	Formamide (%)
EUB338	*Bacteria*	GCTGCCTCCCGTAGGAGT	Cy5	blue	20~50
ARC915	*Archaea*	GTGCTCCCCCGCCAATTCCT	6-Fam	green	20~50
MG1200	*Methanomicrobiales*	CGGATAATTCGGGGCATGCTG	Cy3	red	20
MS1414	*Methanosarcinaceae*	CTCACCCATACCTCACTCGGG	Cy3	red	50
MSMX860	*Methanosarcinales*	GGCTCGCTTCACGGCTTCCCT	Cy5	blue	45

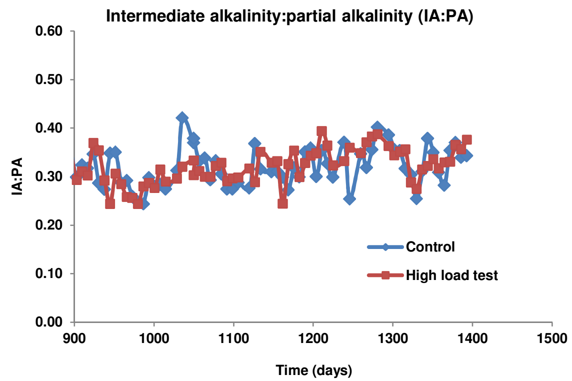
Testing the maximum digester loading

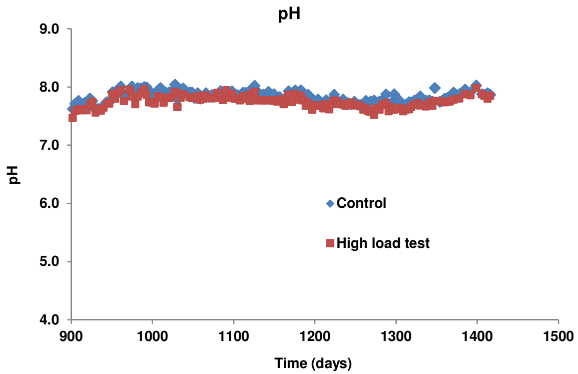




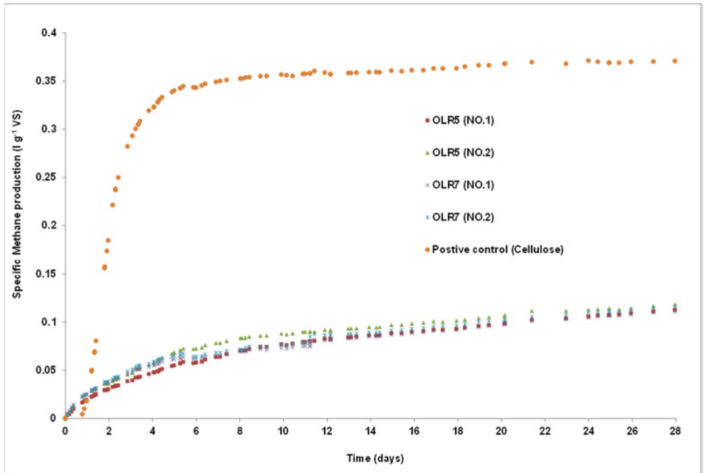
Performance of high load digester (OLR up to 8 kg VS m^{-3} day^{-1})







Digestate RMP compared to control



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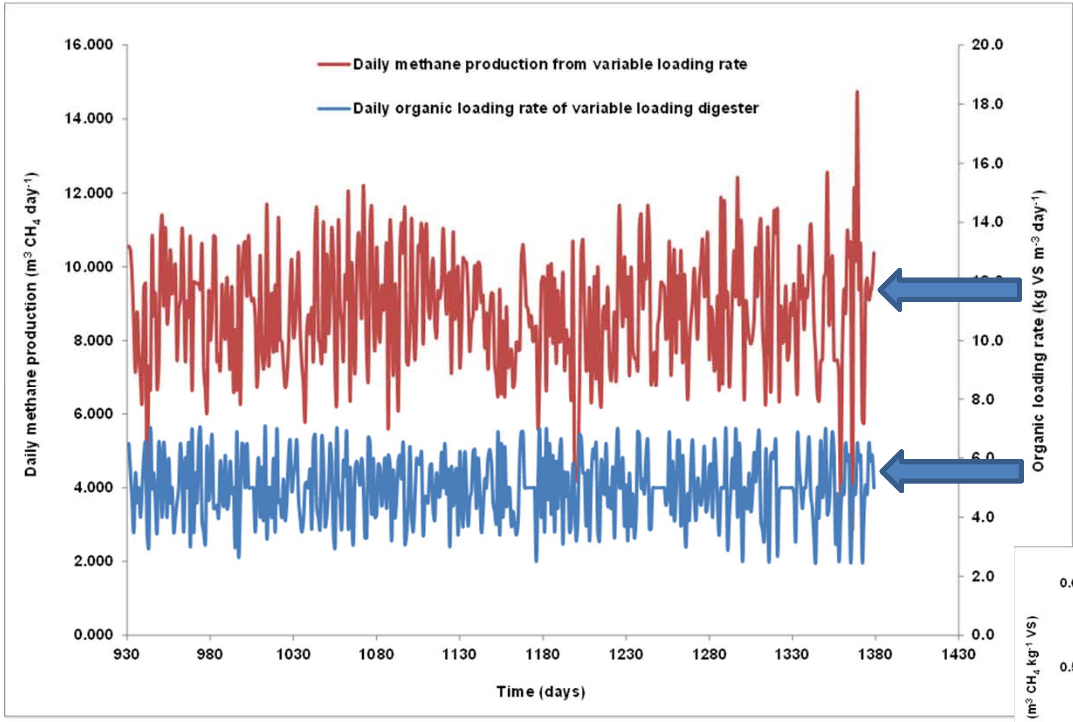
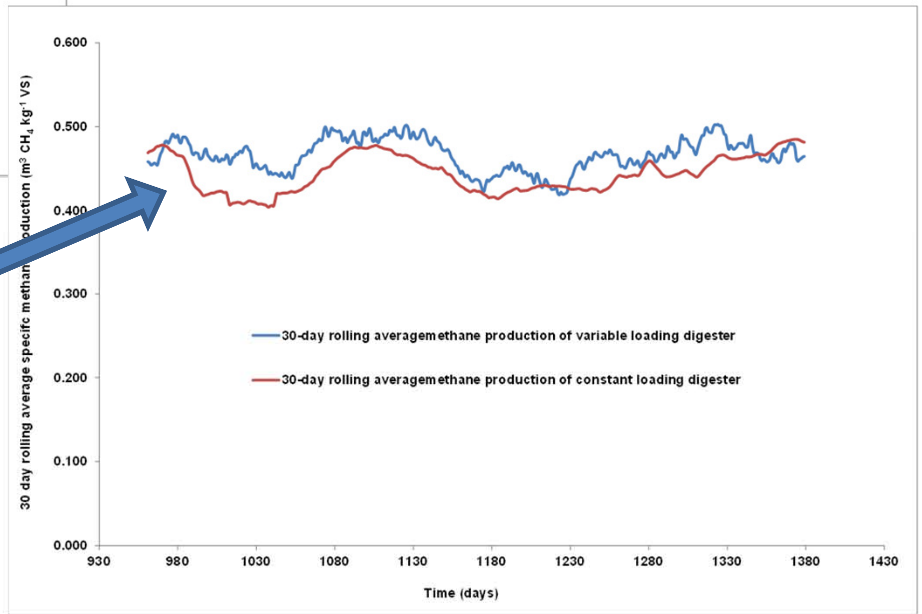
Testing operation under variable load conditions

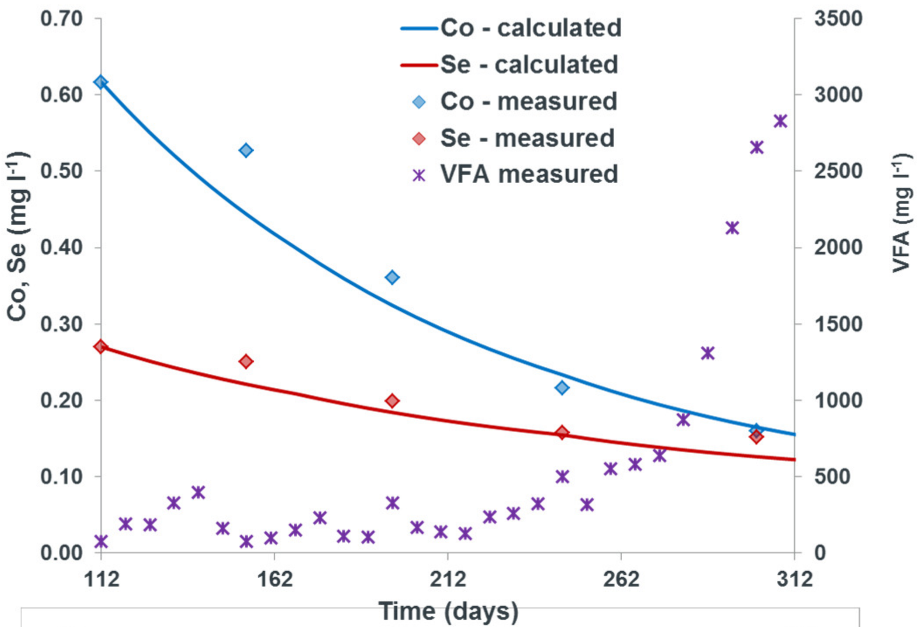


Daily methane production (litres day^{-1})

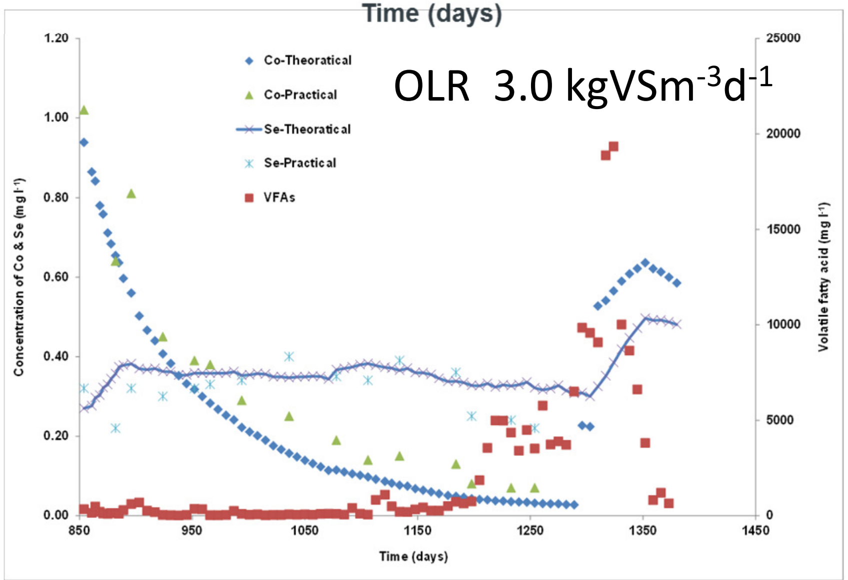
OLR = 5.0 ± 3 kg VS m^{-3} day^{-1}

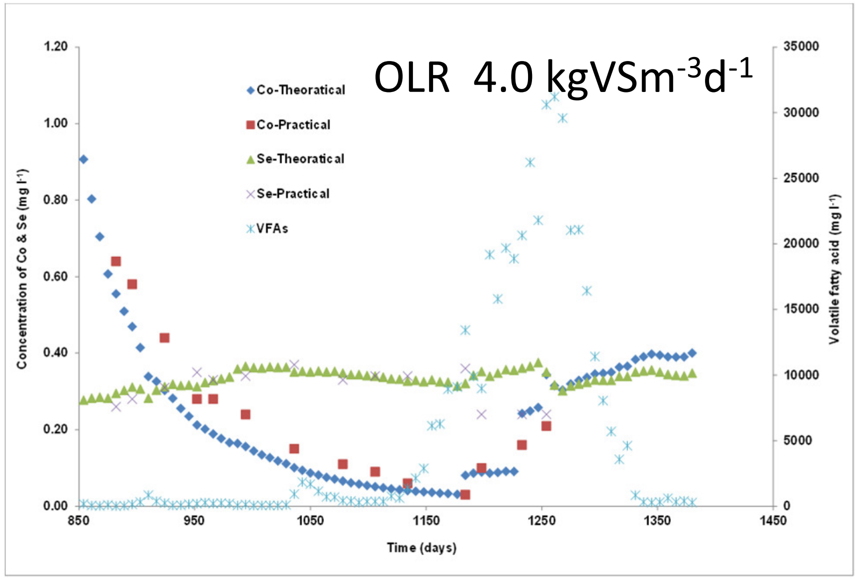
Specific methane production
(30-day rolling average)





Dilute out experiments

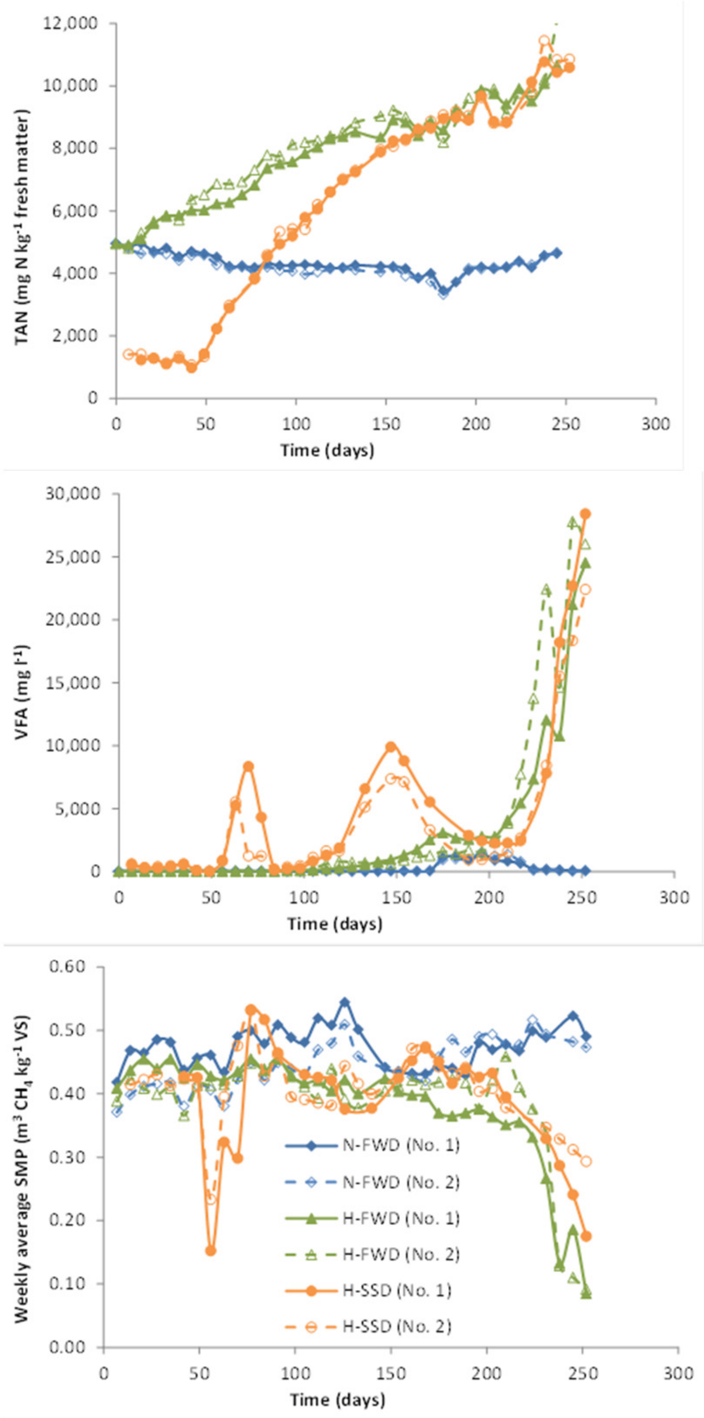




Trace elements requirement

- Selenium and cobalt are the key trace elements needed for long-term stability of food waste digesters in Europe, but are likely to be lacking in the food waste
- Minimum recommended concentrations in food waste digesters for selenium and cobalt are ~0.2 and ~0.35 mg l^{-1} respectively, when running at moderate loading rate
- A total selenium concentration >1.5 mg l^{-1} is likely to be toxic to the microbial consortium
- Food waste is likely to have sufficient Al, B, Cu, Fe, Mn, Zn, Ni, Mo and W, but always check!

Tolerance to ammonia



rea

Increase in ammonia concentration of low ammonia and high ammonia digesters by urea supplementation

Critical concentration at ~ 8gl^{-1} when rapid non-controllable increase in VFA and loss of methane production

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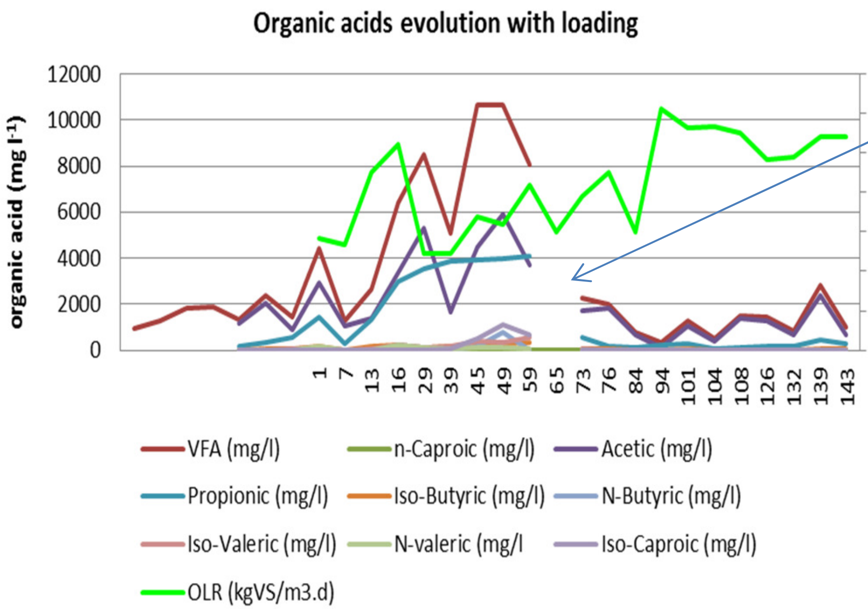
Full-scale digesters

Biocycle 900 m^3 digester

After addition of micronutrients

- VFA reduced from >30000 to <1000 mg l^{-1}
- SMP increased from 380 to 420 m^3 $tonne^{-1}$ VS
- OLR increased to 3.2 kg VS m^{-3} day^{-1}

Andigestion 300 m^3 plant



Substantial reduction in VFA following Se and Co addition

Average composition of food waste as received at the Waterbeach plant

DS % WW	VS % WW	COD g l^{-1}	N-total mg l^{-1}	Co mg l^{-1}	Se mg l^{-1}	Ni mg l^{-1}
18.6	16.7	22.9	6877	0.07	0.04	0.52

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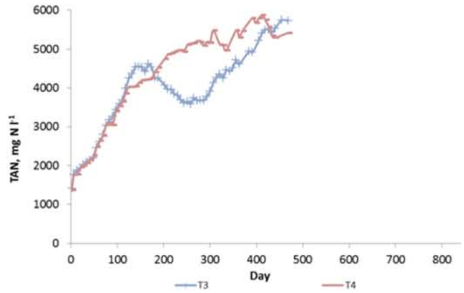
Conclusions from mesophilic digester studies

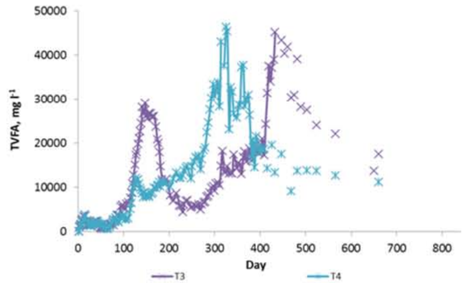
- With proper trace element supplementation, stable operation of food waste digesters is possible with low VFA concentrations at a loading rate of 5 kg VS m^{-3} day^{-1} with volumetric biogas production of 3.8 m^3 m^{-3} day^{-1} and specific biogas production of 0.76 m^3 kg^{-1} VS. Higher loading are possible.
- Prevention of VFA accumulation in the digester by trace element supplementation is necessary, as recovery of a severely VFA-laden digester is not a rapid process even when supplements are added

Thermophilic digestion

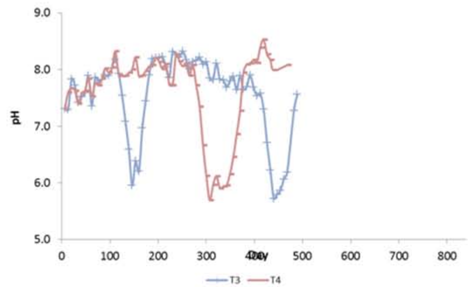
Thermophilic digesters fed on ‘high’ nitrogen food waste



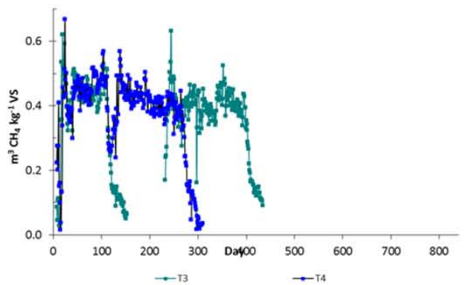
- Acclimatisation from mesophilic to thermophilic conditions
- All digesters given TE supplements
- Rapid increase in TAN
- Necessary to stop feeding T3 due to severe VFA accumulation



- VFA accumulation in T3 which later recovered but then showed further accumulation
- T4 showed steady rise in VFA with a very sharp rise after day ~400

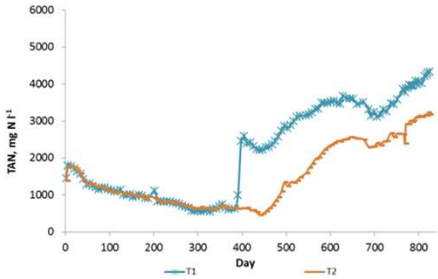


- VFA accumulation broke digester alkalinity leading to severe drops in pH

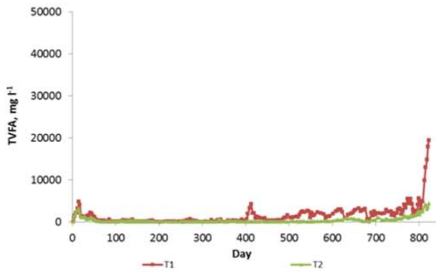


- Loss of biogas production corresponded to high acidity in the digesters which eventually led to non-recoverable failure

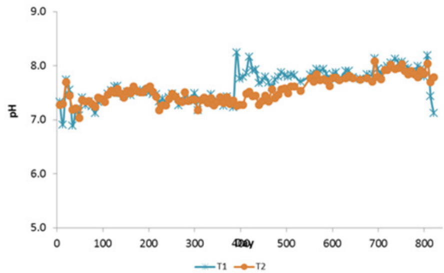
Thermophilic digestion fed on ‘low’ nitrogen food waste



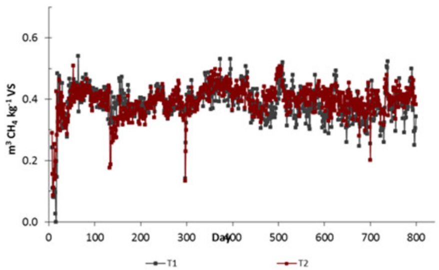
- Low nitrogen food waste prepared from mainly fruit and vegetables
- TE supplemented
- 1 year allowed to acclimate to thermophilic conditions before TAN urea addition



- No VFA accumulation as a result of switching from mesophilic to thermophilic conditions
- VFA start to accumulate as TAN reaches critical threshold concentration

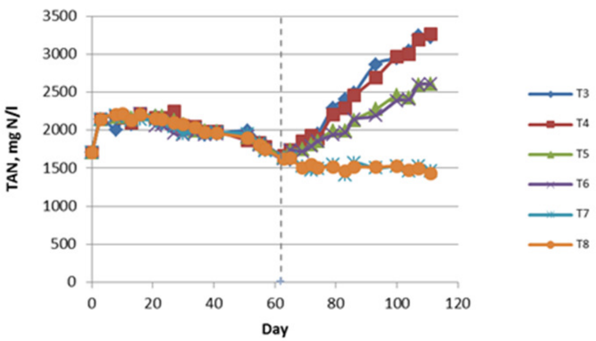


- Addition of urea detected by pH change
- Stable pH

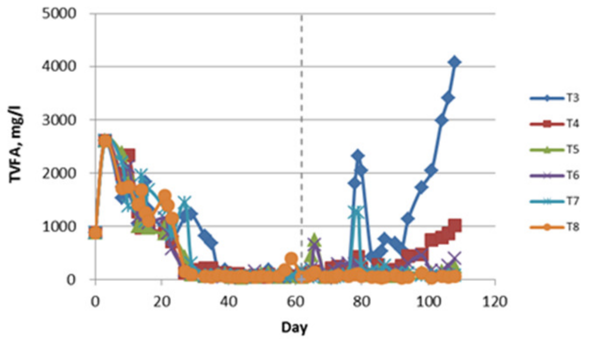


- Stable biogas production

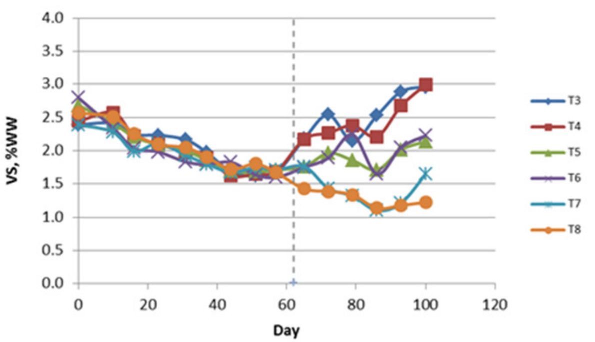
Thermophilic digestion with dilution of ‘high’ nitrogen food waste



- Started with food waste diluted 2 parts water to 1 part food waste
- Dilution changed on day 60 in 2 sets of digester
- 1:1 in T5 and T6
- No dilution in T3 and T4



- VFA starts to accumulate in T3 and T4 when TAN > 2.5 gl^{-1}



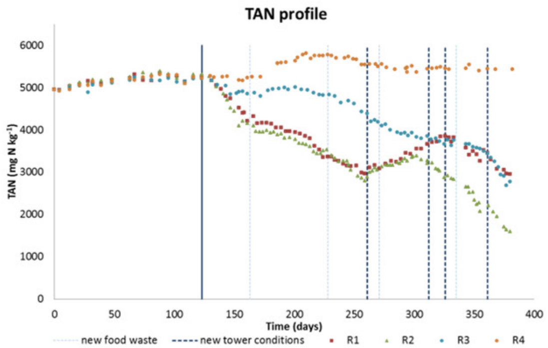
- Dilution also affects the VS concentration in the digester and shortens the HRT
- A dilution of ≤ 1:1 is necessary for stable digestion

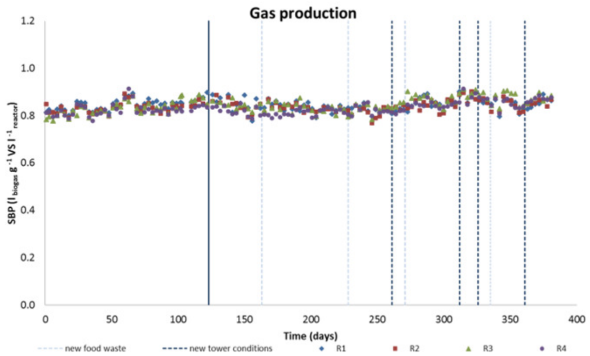
Conclusions from thermophilic digestion studies

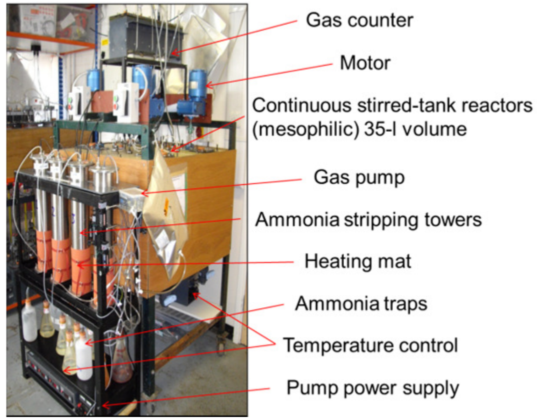
- The threshold inhibition concentration for ammonia is ~2.5 g N l^{-1} TAN
- Failure of digester occurs at ≥ 3.5 g N l^{-1}
- Trace element supplementation is not effective in controlling VFA accumulation in thermophilic digesters
- Food waste can be digested thermophilically by dilution with water, but the ratio must be such as to reduce TAN ≤ 2.5 g l^{-1} which is about a 1:1 dilution

Continuing work

- Ammonia removal in a side stream stripping process successful







- Mass and energy balances on full scale plant

900 m^3 mesophilic digester, buffer tank, gas storage and digestate storage at the South Shropshire plant

Two 3500 m^3 thermophilic digesters at the Valorsul AD plant in Lisbon

	Temp °C	OLR kg VS m^{-3} d^{-1}	SMP m^3 CH_4 tonne VS^{-1}	VMP m^3 m^{-3} reactor day^{-1}	$EROEI_{el}$ (electric)	EROEI (heat & electric)
Biocycle	40	2.5	422	1.07	3.5	4.7
Valorsul	51	1.6	409	1.10	2.2	-

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Department for Environment Food and Rural Affairs

…and to EU FP7 VALORGAS project

SEVENTH FRAMEWORK PROGRAMME

VALORGAS