Food waste digestion

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Why separate domestic food waste?

- Food waste between 20 – 30% of kerbside collected material
- Removes wet and putrescible waste and makes recycling of dry wastes easier
- Reduces vermin and smell problems
- Biofertiliser is free of contaminants and can be applied to agricultural land
- Keeps the process simple

Composition of collected kitchen waste

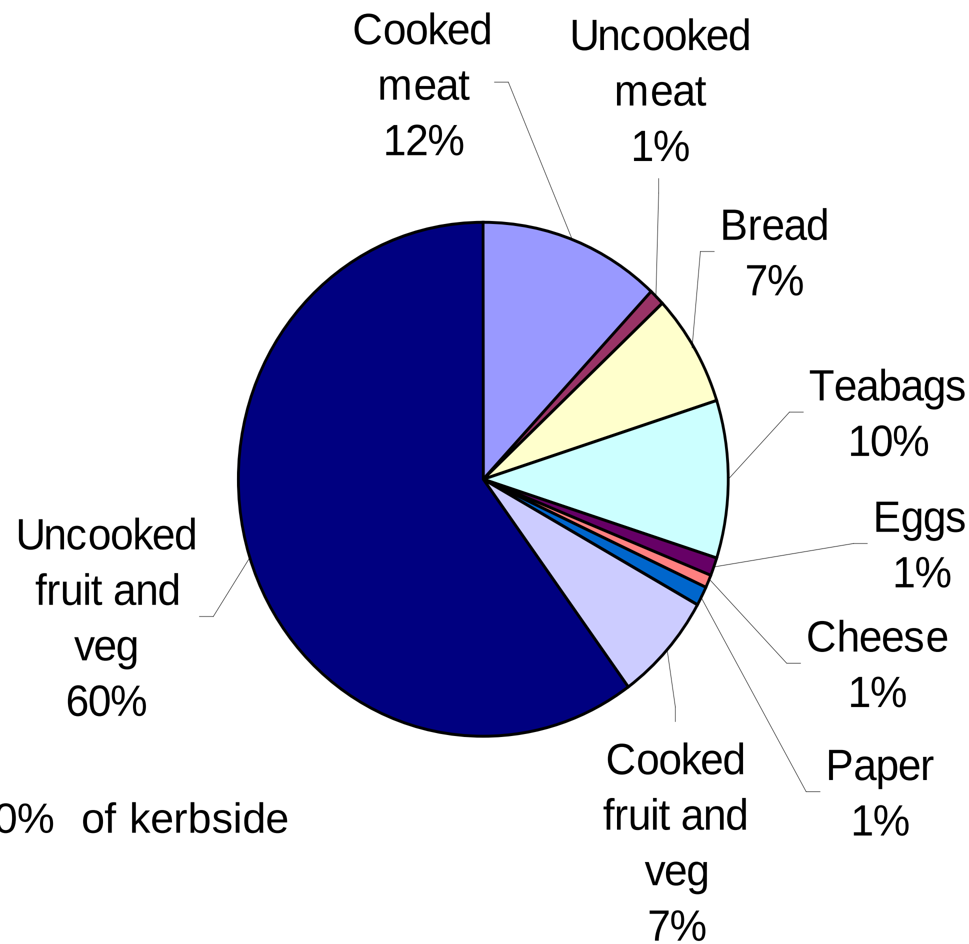
2.91 kg household^{-1} week^{-1}

TS = 23%

VS = 93% of TS

$C_{252}H_{39}O_{132}N_{18}S_1$

C : N ratio 14:1



UK estimates kitchen food waste is 20-30% of kerbside collected domestic waste

Optimisation of anaerobic digestion for food waste and mechanically recovered BMW

Background

- Part of a larger study to evaluate the co-digestion of organic biodegradable fractions of MSW with a range of commercial and industrial wastes
- MSW waste streams chosen for the study were: were source-segregated food waste (ssFW) and post-collection mechanically-sorted biodegradable municipal waste (msBMW)
- Presentation looks at the performance of these two substrates in both batch and semi-continuous digestion trials

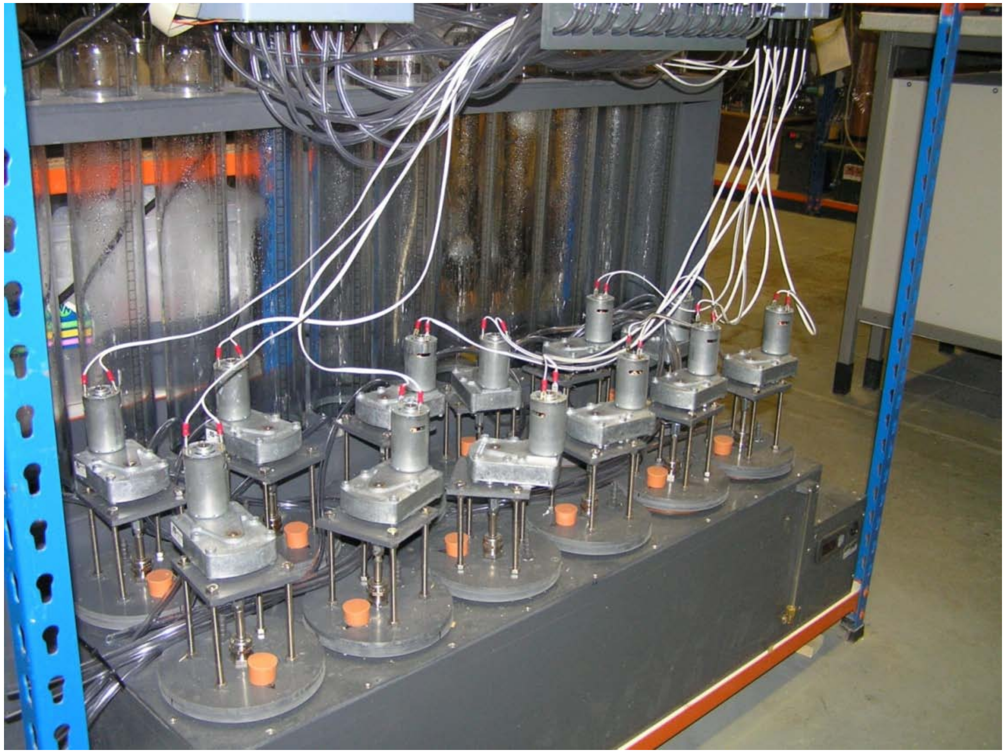
Objectives

- To derive data on energy yield
- To assess the digestate for stability and potentially toxic elements
- From chemical and calorimetric analysis of the wastes to determine the energy conversion efficiency of the digestion process

Methodology

- Representative samples of both waste streams taken
- Further particle size reduction of the food waste stream
- All digesters used were of a CSTR design and had working volumes of 1.4, 4, 35 and 75 litres.
- Operation was at 35 ^{o}C, continuous gas flow measurement, daily feeding for semi-continuous operation

1.4-litre batch fed digesters



75-litre digesters

Waste characteristics

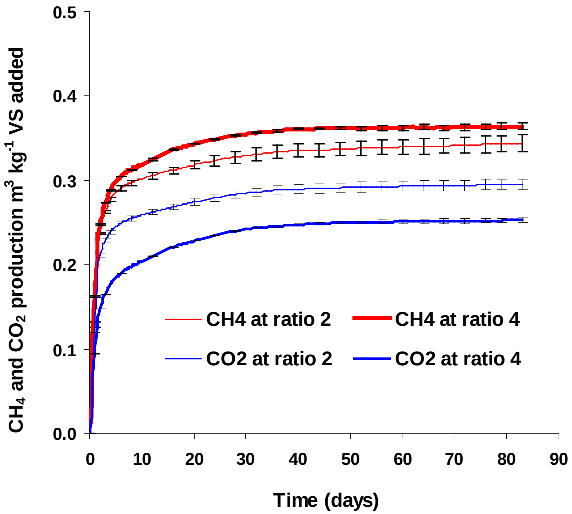
	Food waste	BMW
pH (1:5)	4.71 ± 0.01	6.39 ± 0.01
TS (% wet weight (WW))	23.74 ± 0.08	52.83 ± 0.63
VS (% WW)	21.71 ± 0.09	33.55 ± 0.63
VS (% of TS)	91.44 ± 0.39	63.52 ± 1.89
Total Organic Carbon (TOC) (% of TS)	47.6 ± 0.5	34.8 ± 1.1
Total Kjeldahl Nitrogen (TKN) (% of TS)	3.42 ± 0.04	1.39 ± 0.08
TOC / 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 methane potential tests

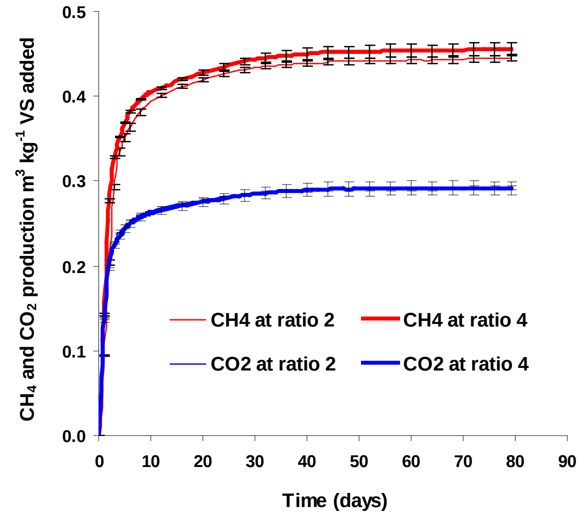
Tests conducted in triplicate with positive controls.

Mechanically sorted BMW = 0.364 m^3 CH_4 kg^{-1} VS_{added}

Food waste = 0.456 m^3 CH_4 kg^{-1} VS_{added}



Mechanically-sorted BMW

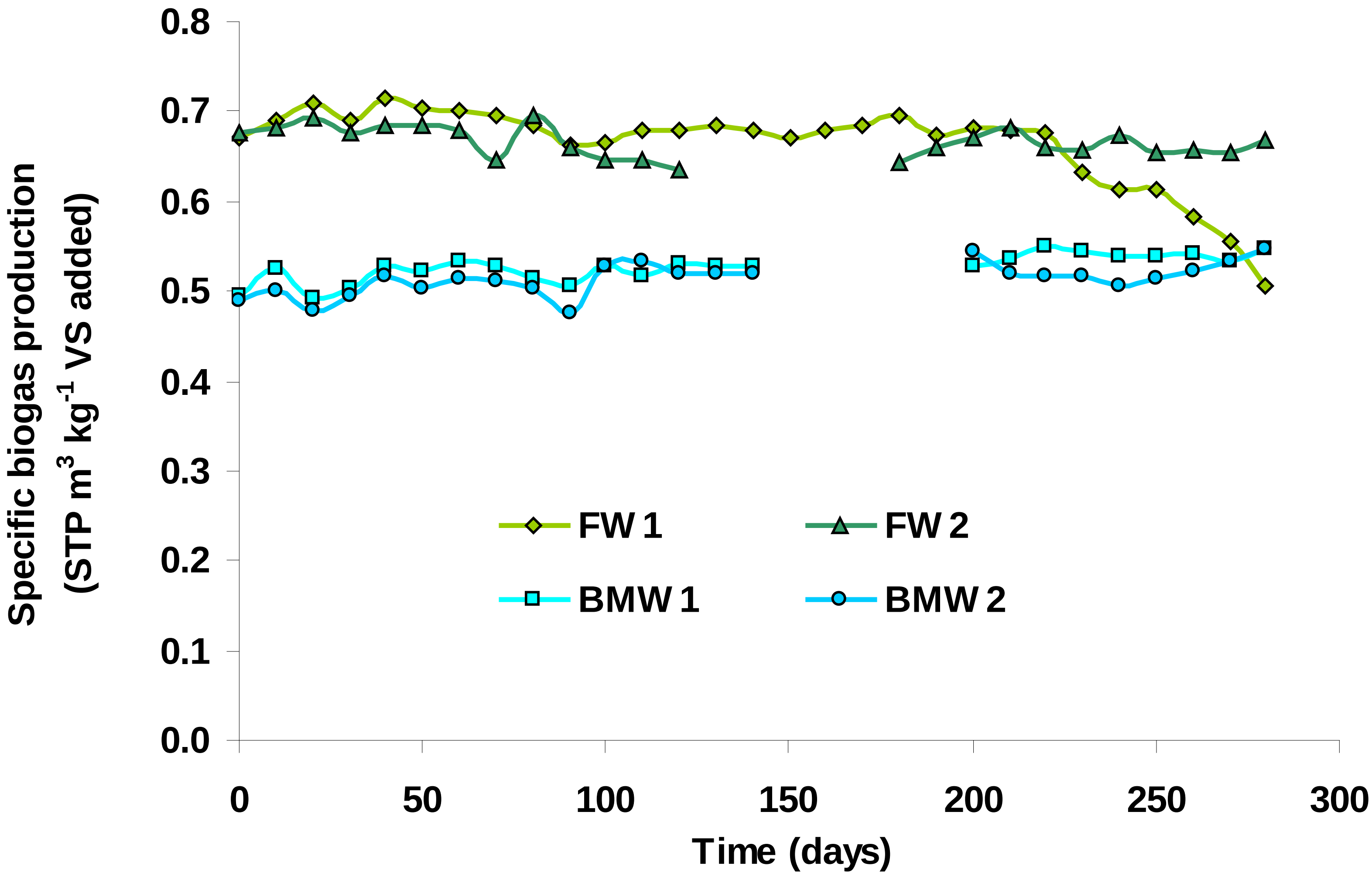


Source-segregated food waste

35-litre semi-continuous trial

- Used both waste streams
- Daily feeding at an organic loading rate of 2.0 g VS l^{-1} d^{-1}
- Experiment ran for 284 days
- Some data interruptions as digestate removed as inoculum for other experiments, removal compensted for by volume proportional feed
- Digesters operated to give a solids retention time of 30 days by solids liquid separation and liquor return

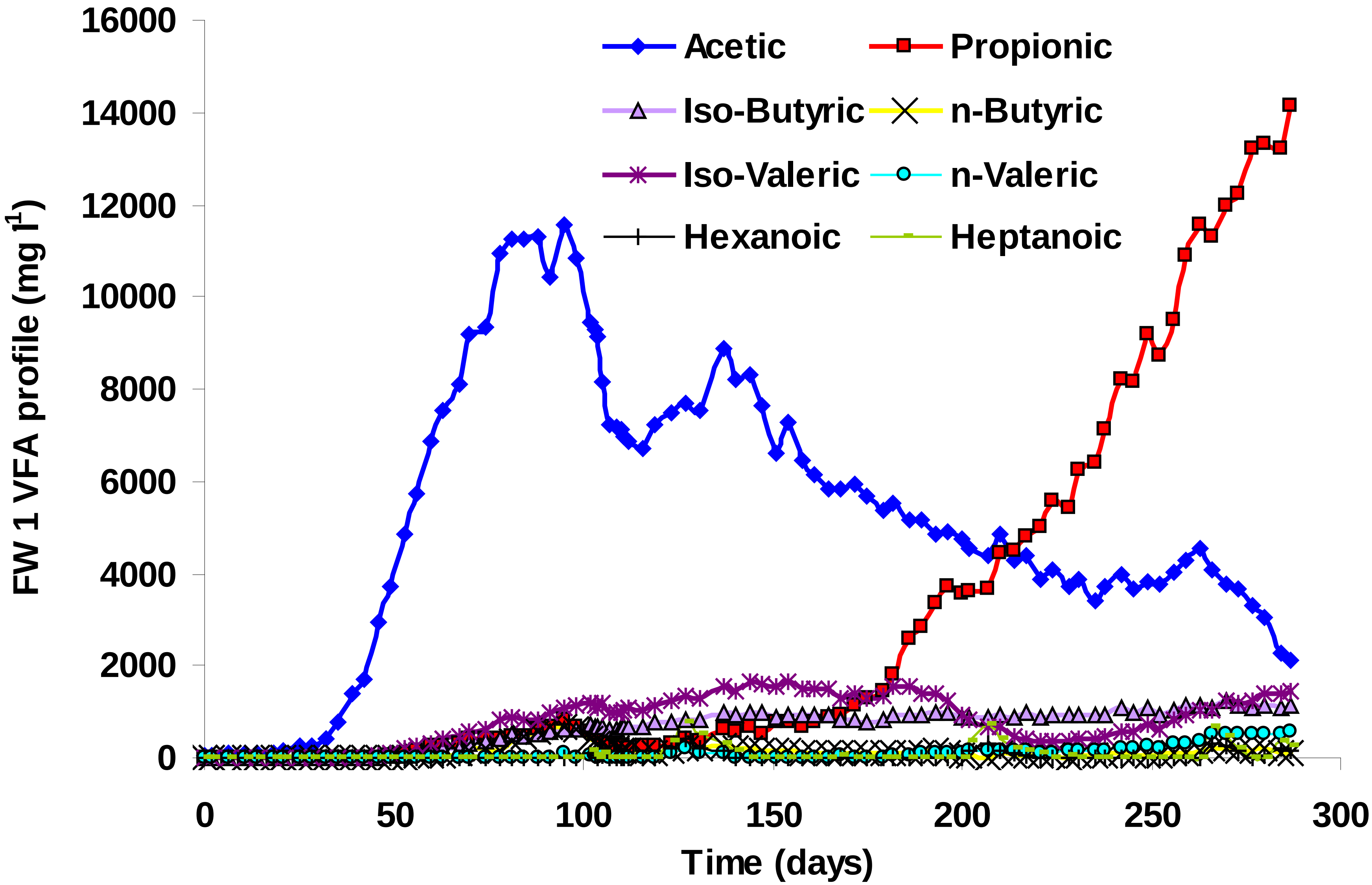
35-litre semi-continuous trial



35-litre summary results

- BMW
  - Specific biogas potential 0.529 $m^3\ kg^{-1}\ VS_{added}$
  - Specific methane potential 0.304 $m^3\ CH_4\ kg^{-1}\ VS_{added}$
  - Specific methane potential 86% of BMP value
  - Ammonia = 1400 $mg\ l^{-1}$, VFA < 100 $mg\ l^{-1}$, pH 7.5
- Food waste
  - Specific biogas potential 0.695 $m^3\ kg^{-1}\ VS_{added}$
  - Ammonia ≈ 4000 $mg\ l^{-1}$, VFA up to 20000 $mg\ l^{-1}$, pH 7.7
  - Rising VFA and severe foaming

VFA in 35-litre FW digester



4-litre digester kinetic study

- Experiment carried out in duplicate
- 425 days duration for BMW
- 329 days for food waste
- Used inoculum from 35-litre digesters
- Sequential raising of loading rate
- Assessed volumetric methane production and digester stability parameters

Results of 4-litre study

- Food waste digesters failed after one retention time with pH < 6, methane concentration < 10%
- Monitoring of VFA concentrations continued until day 329 by which time the accumulated VFA had degraded
- Loading on BMW digesters successfully increased to 4 kg VS l^{-1} d^{-1}
- Volumetric biogas production 2.1 m^3 m^{-3} d^{-1}
- VFA concentration less than 150 mg l^{-1}
- TAN 1600 mg l^{-1}, pH 7.4

75-litre FW digester results

- Started from fresh sewage sludge inoculum
- After 120 days VFA began to accumulate and reached 4000 mg l^{-1} by day 270
- Changing VFA profile from predominantly acetic to predominantly propionic acid
- Performance parameters for pseudo steady state
    - SMP 0.425 STP m^3 kg^{-1} Vs_{added}
    - 86.5% VS converted to biogas,
    - 60.6% methane in biogas,
    - pH rising to 8.1
    - TAN rising to 4900 mg l^{-1}

Stability and PTE

Food waste digestate with high VFA levels showed high residual methane potential in BMP tests with sewage sludge inoculum

Food waste digestates were very low in PTE and physical contaminants

BMW digestate had a low residual methane potential

BMW digestate failed PAS110 criteria for PTE, and showed high levels of physical contamination

Digestate nutrient concentrations reflected those in the feedstock

Conclusions

Mechanically-sorted BMW

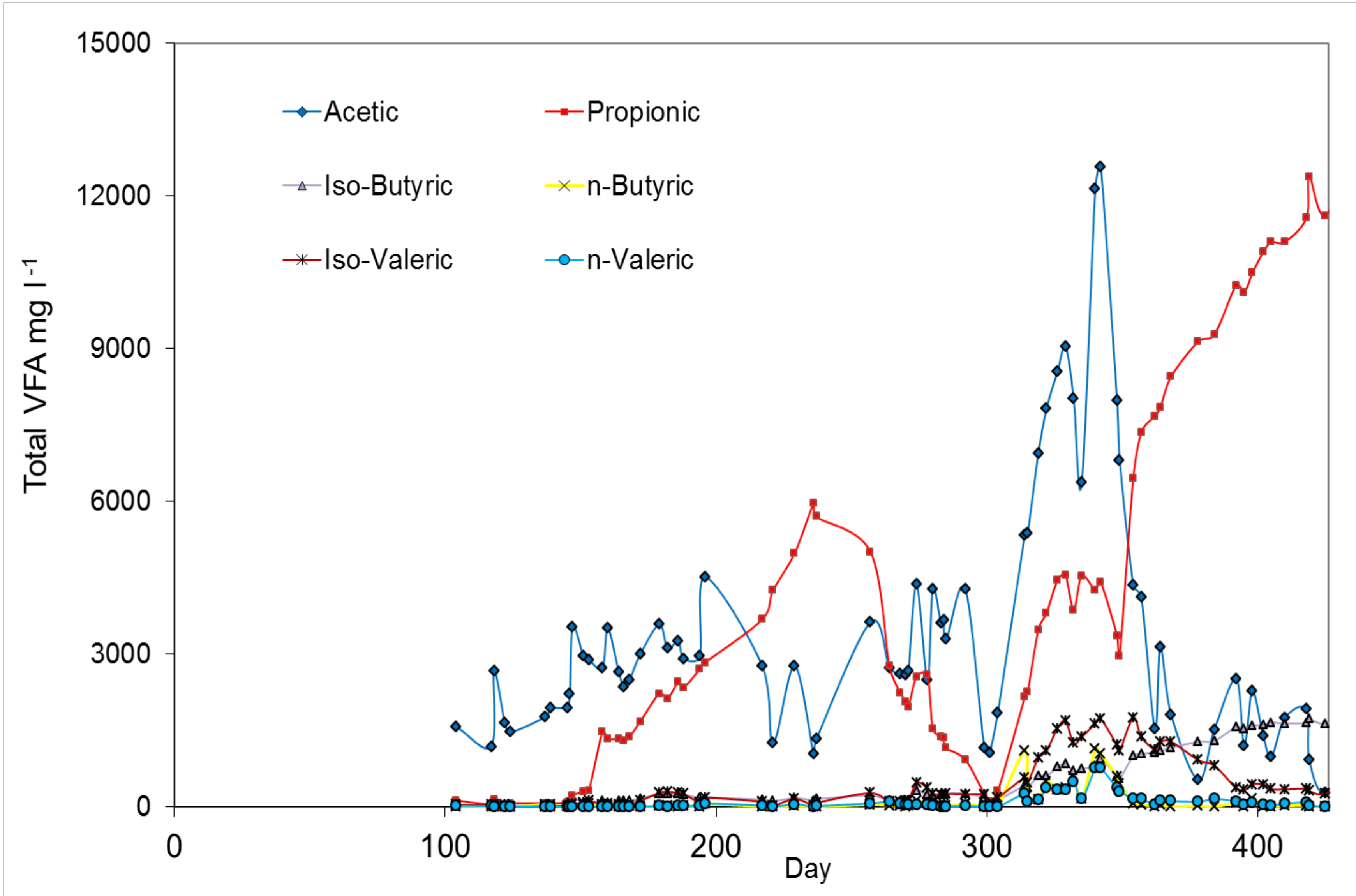
- BMW is a stable substrate for AD
- Because of its relatively low biodegradability it may also be suitable for ‘dry’ digestion systems as digester solids can reach 17% at high loadings
- Concentrations of certain potentially toxic elements exceeded the PAS 110 limit
- While this does not rule out land application for non-agricultural purposes, with the presence of plastics and other physical contaminants it limits the potential of the digestate as a high-value product.

Conclusions continued

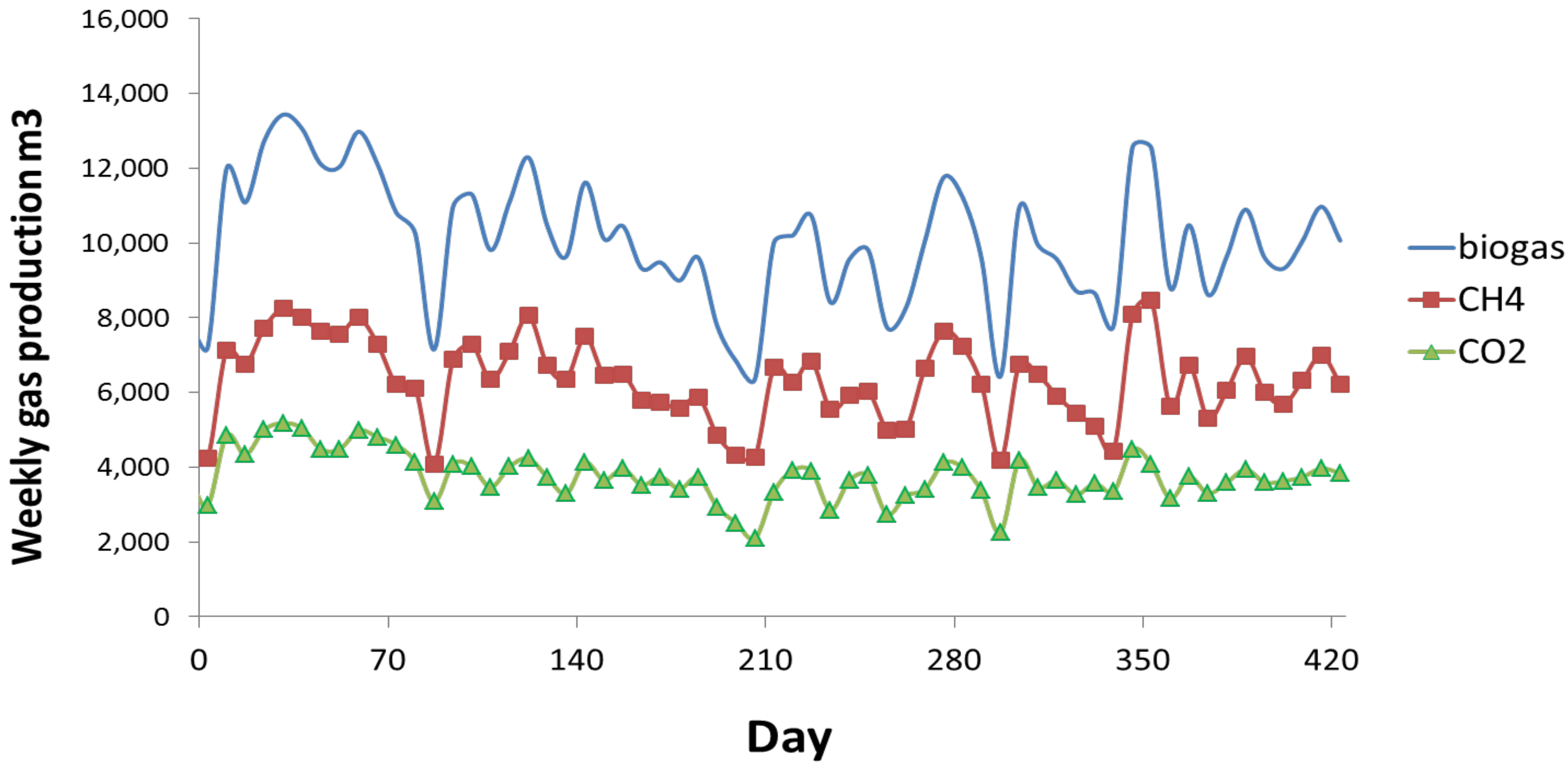
Source-segregated food waste

- Food waste has a very high specific methane yield
- The high nitrogen content results in high ammonia levels that lead to raised VFA concentrations in the digestate probably as a result of inhibiting the acetoclastic methanogens and thus restricting the metabolic pathways to methane production.
- In these conditions the organic loading may be limited: the maximum that could be achieved in this research was 2 kg VS m^{-3} d^{-1}.

The Real World



Acetic
Propionic
Iso-Butyric
n-Butyric
Iso-Valeric
n-Valeric
Total VFA mg l -1
Day
15000
12000
9000
6000
3000
0
0
100
200
300
400



Weekly gas production m3
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
0
70
140
210
280
350
420
Day
biogas
CH4
CO2

Theory

Facts, speculation and interpretation

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 reductase enzyme system	→	Are these commonly added in trace element formulations? What is the concentration in food waste?
Can we prove the theory	→	Will need to look at combination of TE trials, metabolic assays and serotyping

Solutions

- Manipulation of the methanogenic population by selective trace element addition so that it can function effectively by the hydrogenotrophic route without the accumulation of propionic acid

- Reduce the ammonia concentration in the digester so that the acetoclastic methanogenic route is compromised

Trace element supplementation for stable food waste digestion

Research aim

To optimise a trace element supplementation strategy

- Identify essential trace elements for stable food waste digestion
- Determine the optimal trace element supplementation strength

Research approaches

- Batch flask trials for screening purpose
- Semi-continuous digester operation to monitor the long-term effect

Key parameters

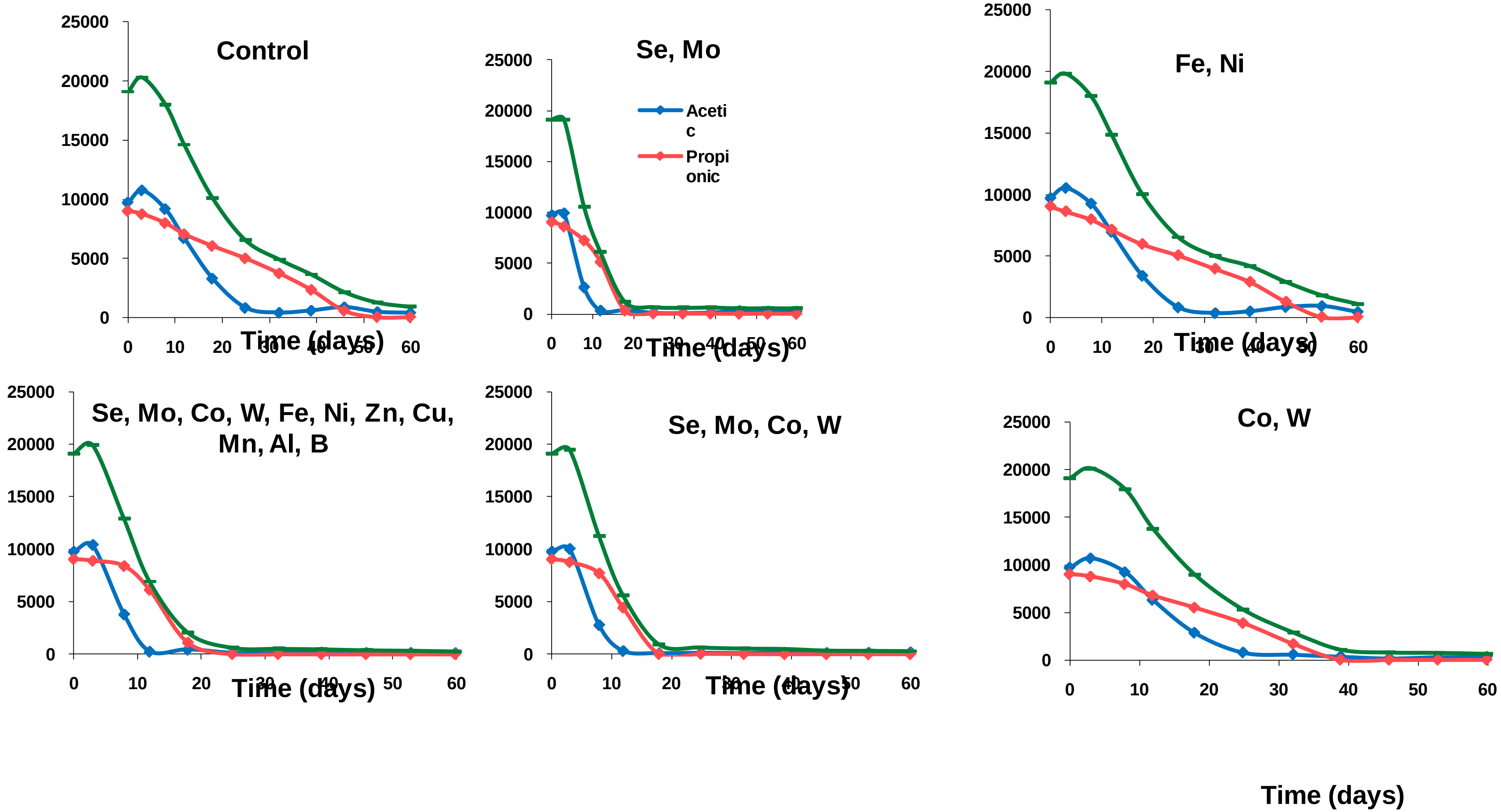
- Trace elements (TE) concentrations
- Volatile fatty acids (VFA) concentrations (*e.g.* acetic acid and propionic acid)

Batch screening tests

Fractional factorial design

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

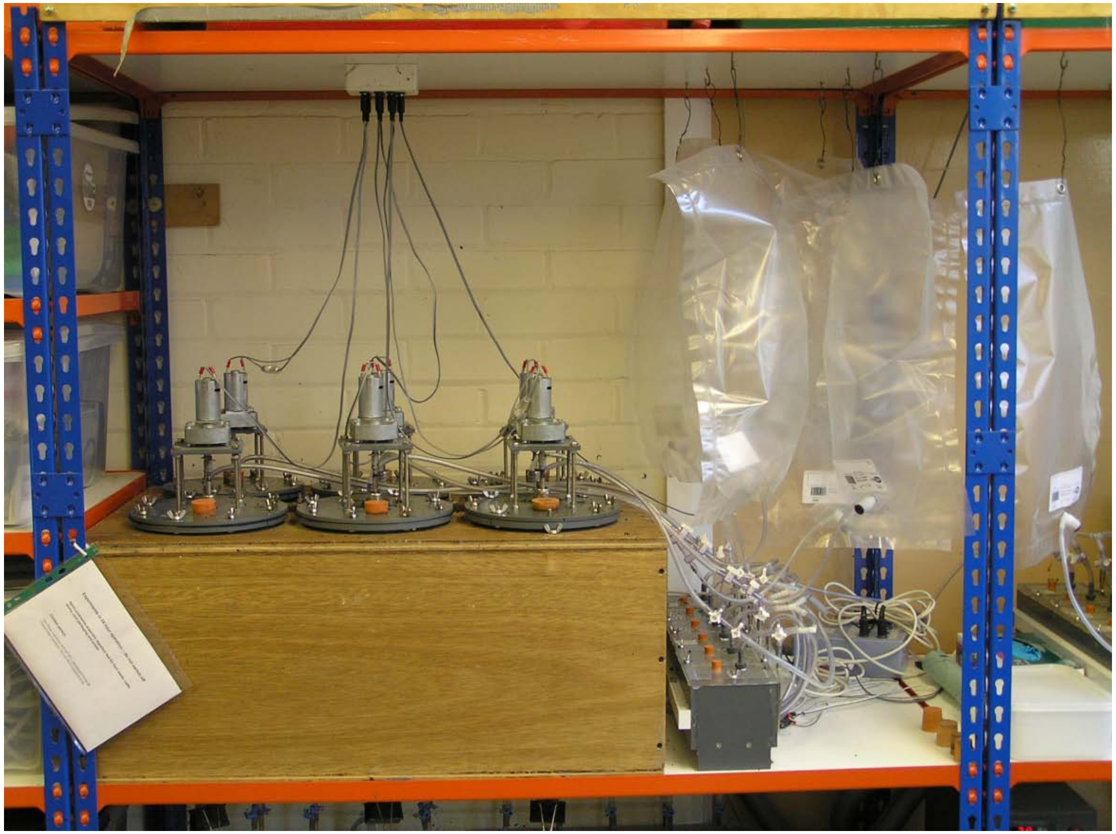
Acetic and Propionic acids degradation profiles



Essential trace elements for food waste digestion

Tier	Trace element	Compound	Dosing strength (g $tonne^{-1}$)
1^{st}	Selenium (Se)	Na_2SeO_3	0.2
	Molybdenum (Mo)	$(NH_4)_6Mo_7O_{24}\cdot 4H_2O$	0.2
2^{nd}	Cobalt (Co)	$CoCl_2\cdot 6H_2O$	1.0
	Tungsten (W)	$Na_2WO_4\cdot 2H_2O$	0.2
3^{rd}	Iron (Fe)	$FeCl_2\cdot 4H_2O$	5.0
	Nickel (Ni)	$NiCl_2\cdot 6H_2O$	1.0
4^{th}	Zinc (Zn)	$ZnCl_2$	0.2
	Copper (Cu)	$CuCl_2\cdot 2H_2O$	0.1
	Manganese (Mn)	$MnCl_2\cdot 4H_2O$	1.0
	Aluminium (Al)	$AlCl_3\cdot 6H_2O$	0.1
	Boron (B)	H_3BO_3	0.1

Semi-continuous anaerobic digestion trials

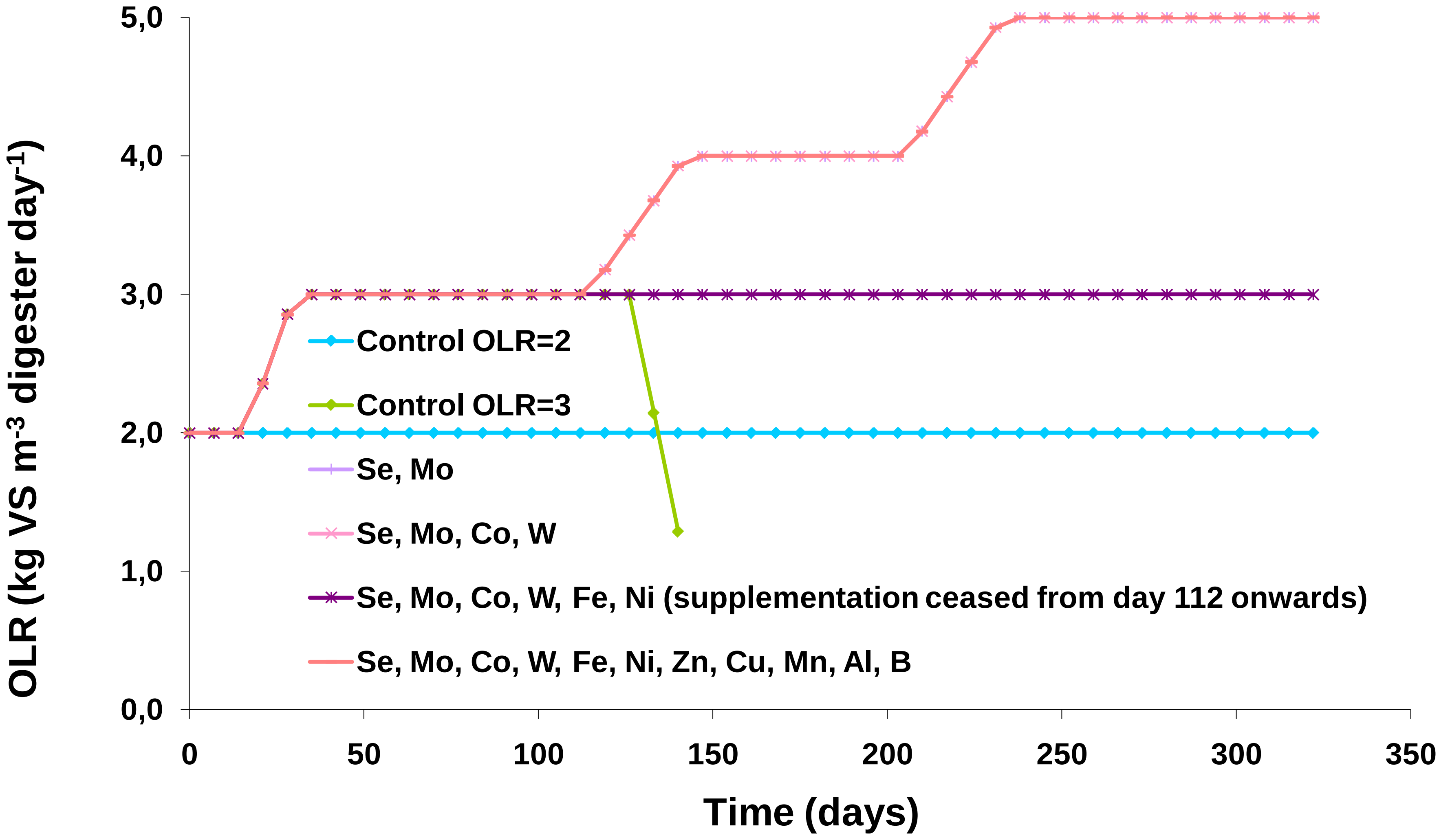


Supplemented with:

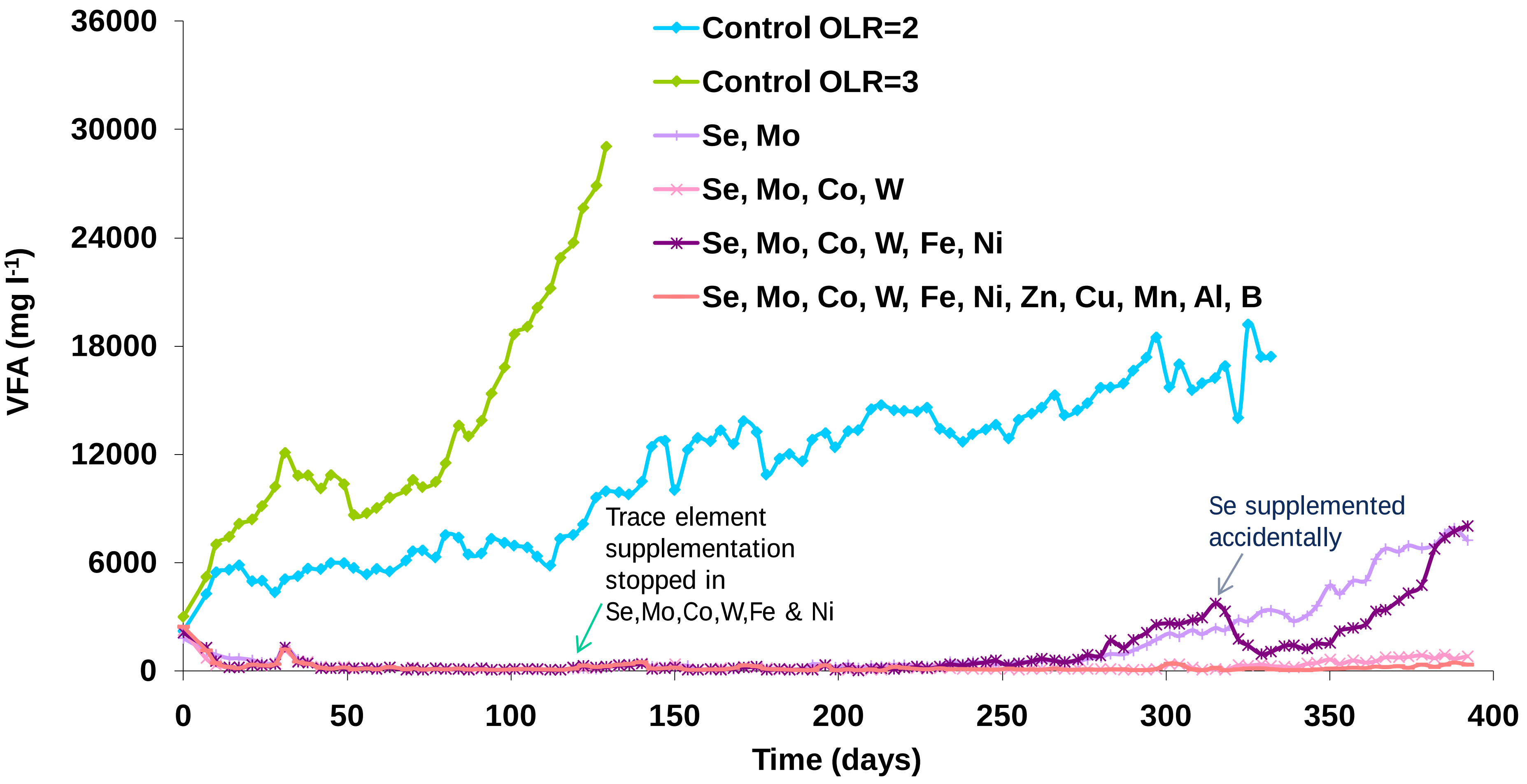
- **Trace element combinations**
- **Single trace element**

Supplementation with combinations of trace elements

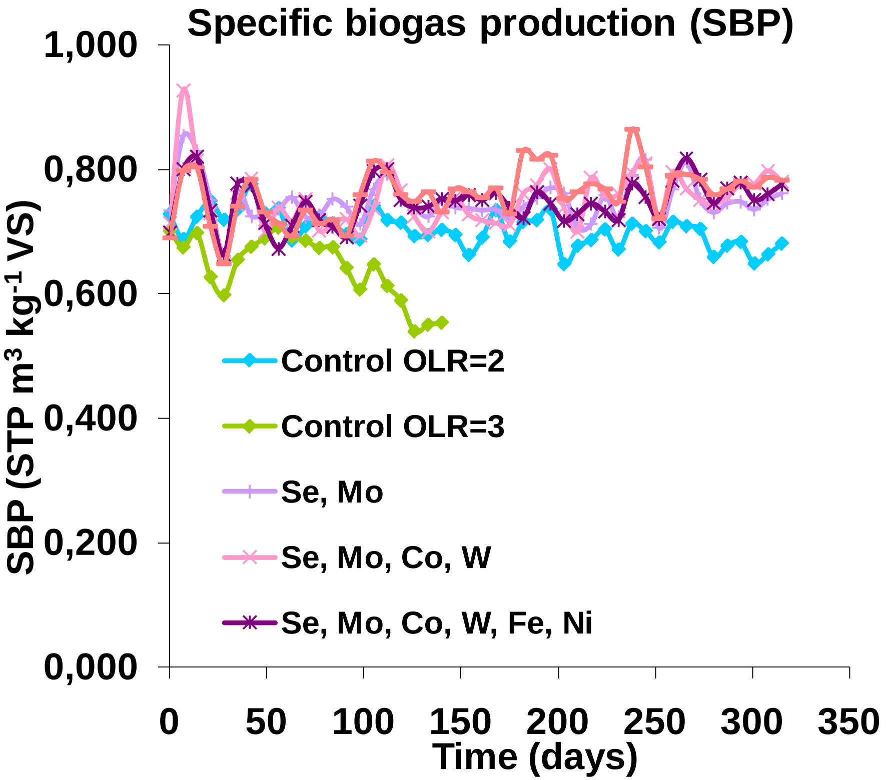
Organic loading rate (OLR)

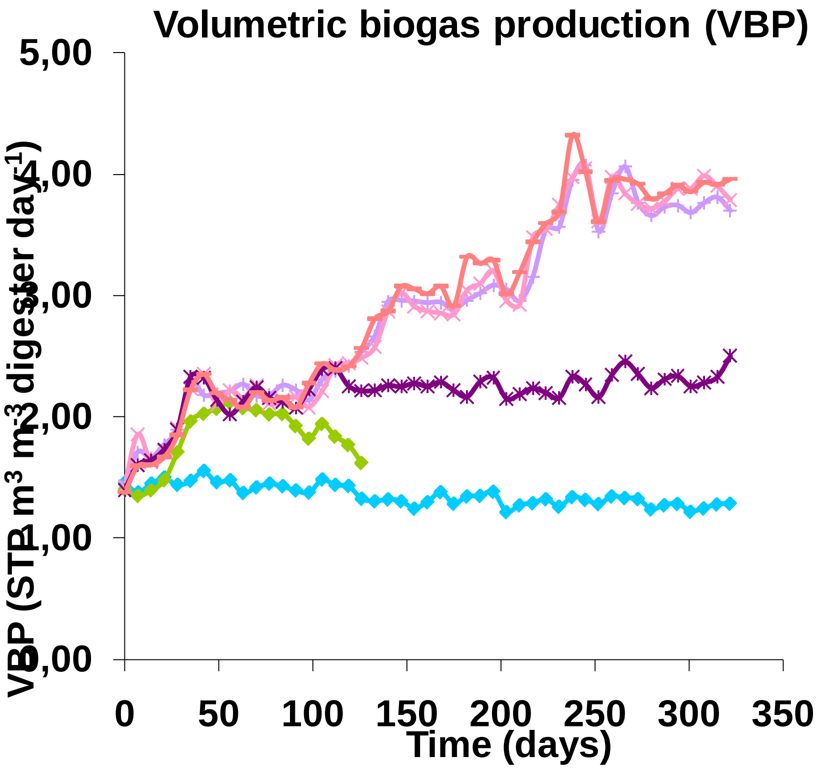


Volatile fatty acids profiles

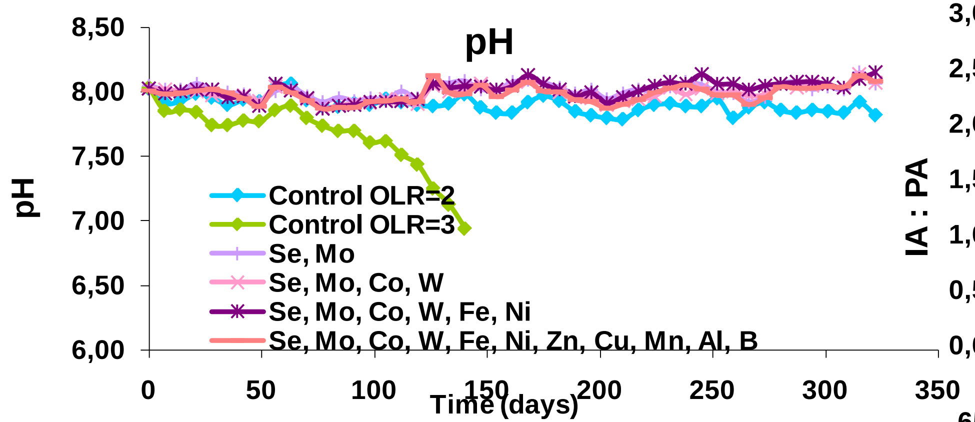


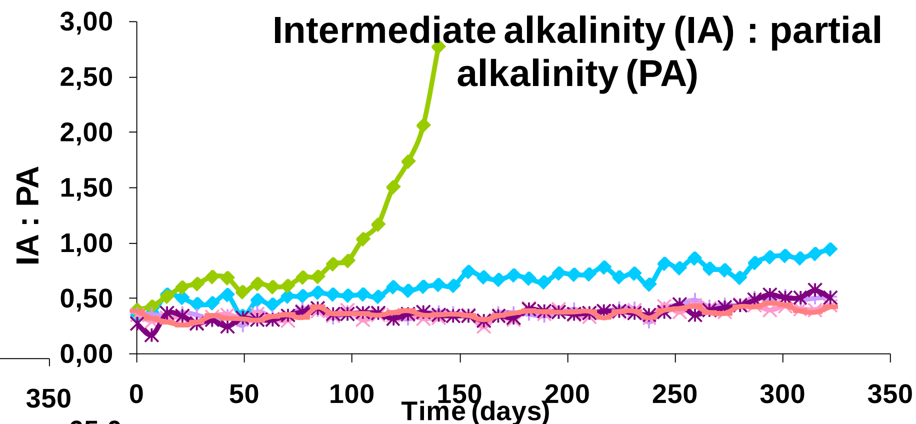
Digestion efficiency

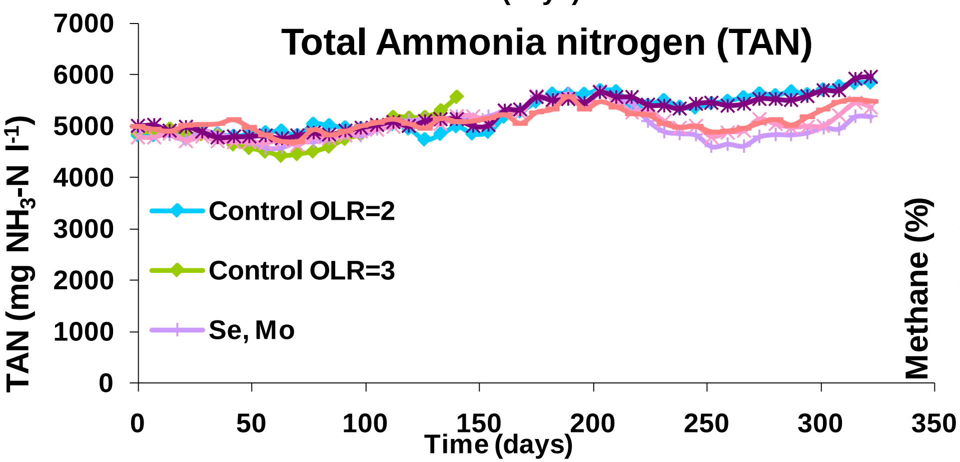


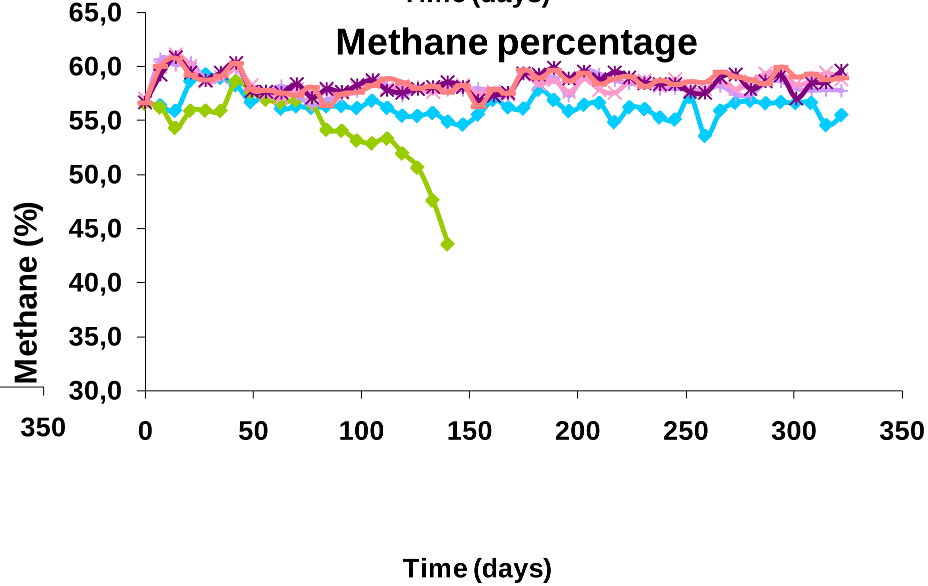


Other digester parameters

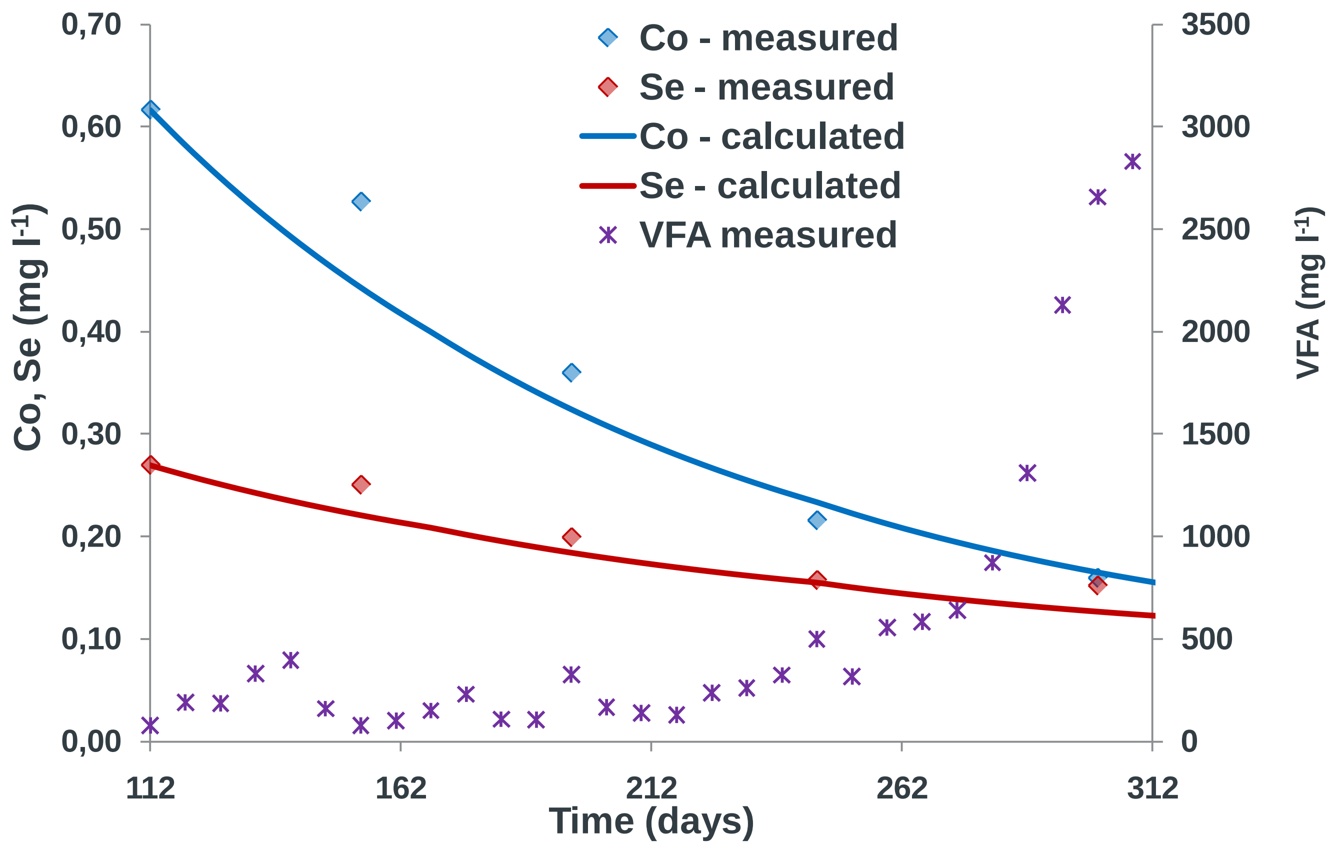


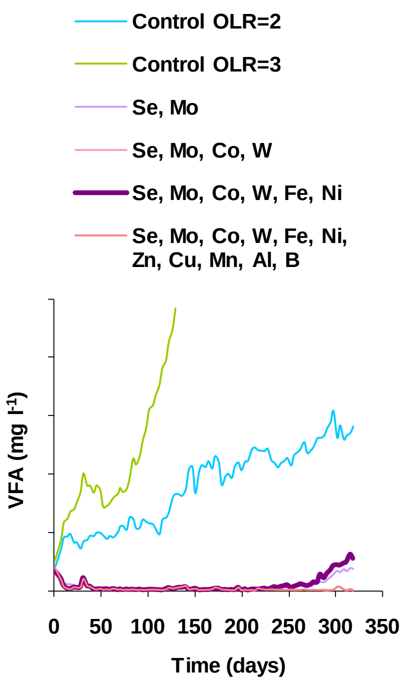






Co and Se dilute-out curves - VFA profile

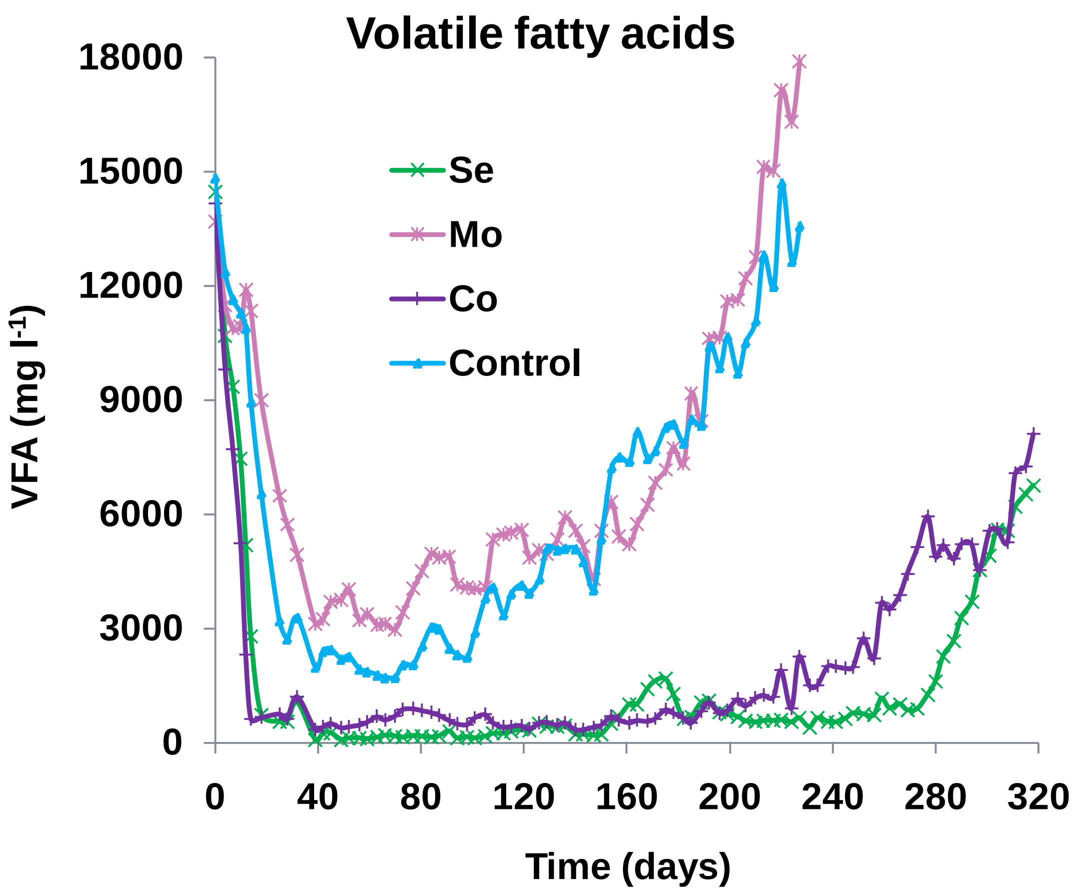




Single trace element supplementation

Recovery of digesters using Se, Mo, and Co

Parameters	Values
OLR (kg VS m^{-3} d^{-1})	2
TAN (mg NH_3-N l^{-1})	5400 → 6200
Methane (%)	59 → 54
SBP (STP m^3 kg^{-1} VS)	0.79 → 0.69
VBP (STP m^3 m^{-3} d^{-1})	1.6 → 1.4



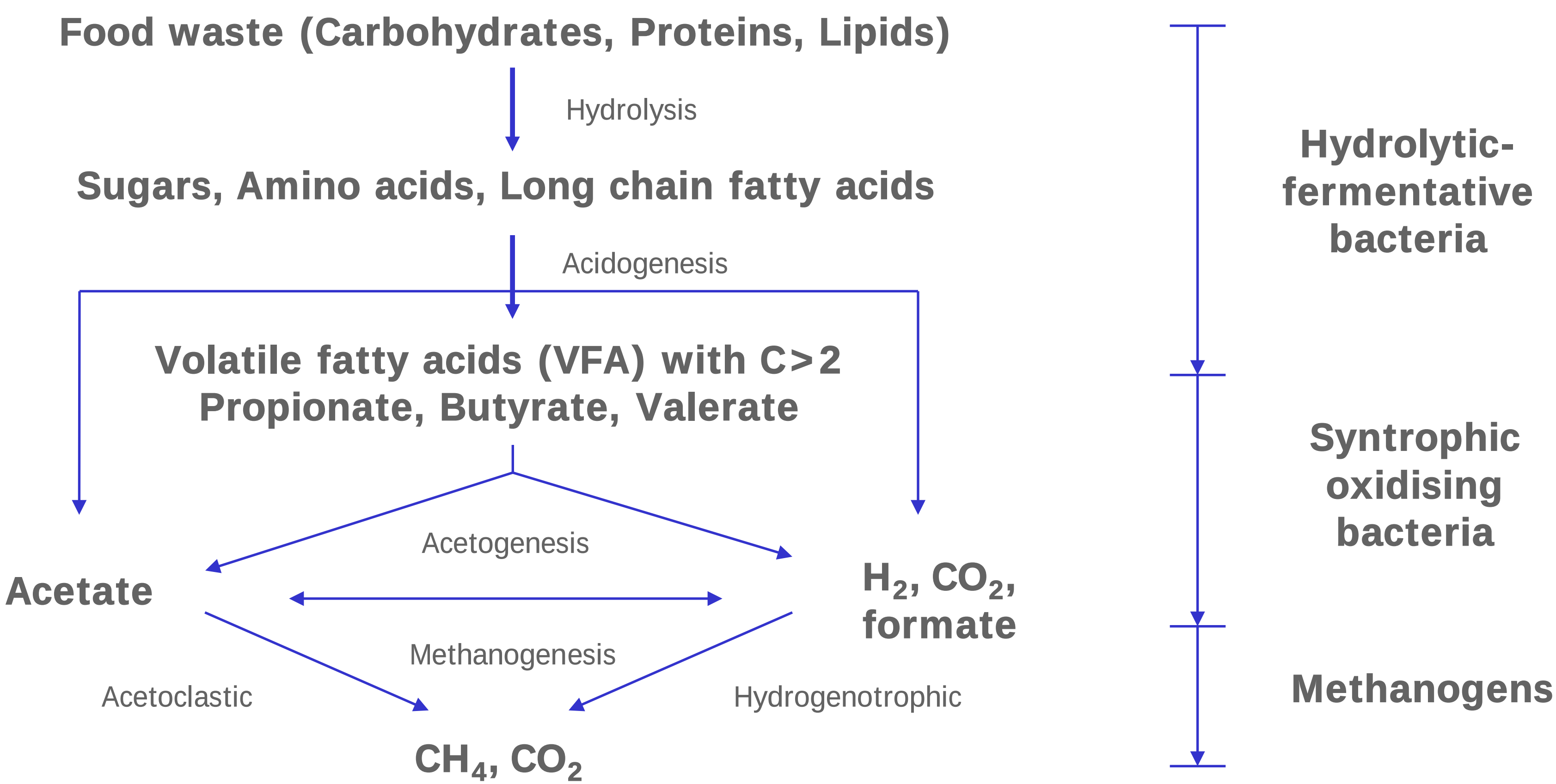
TE required vs TE in the food waste

	Minimum requirement at a moderate loading rate	Hackney, London	Luton, South Bedfordshire	Ludlow, Shropshire
Co	0.22	0.090±0.049	0.017±0.002	<0.060
Se	0.16	0.10±0.08	0.28±0.14	<0.07
TKN	-	8100	7400	8100

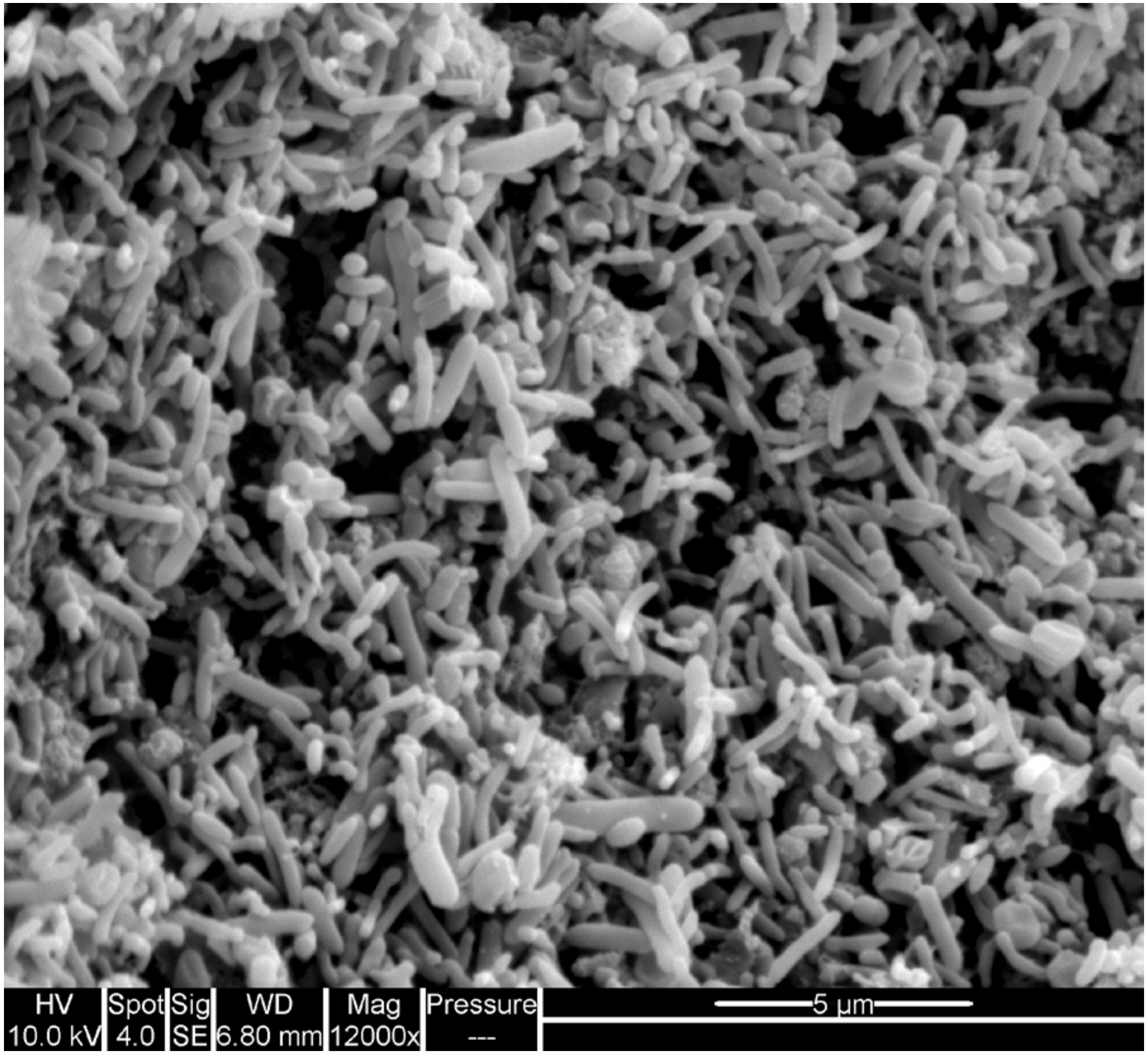
Unit: mg kg^{-1} fresh matter

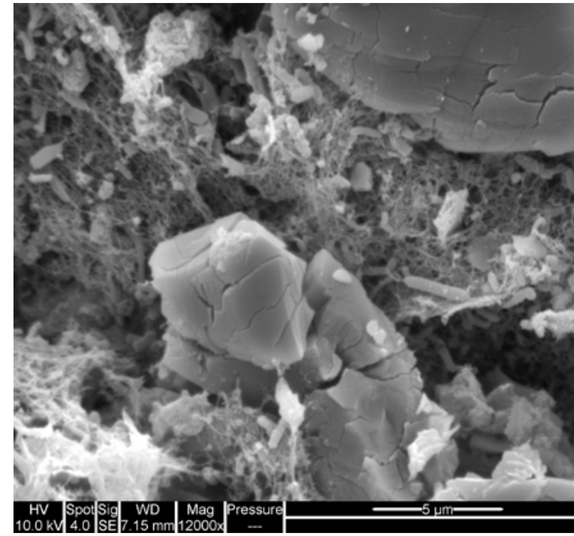
Microbial community structure analysis

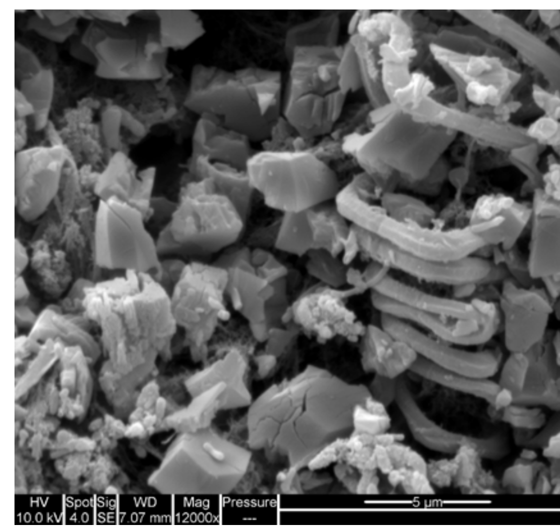
Anaerobic conversion process



Density gradient centrifugation – SEM images



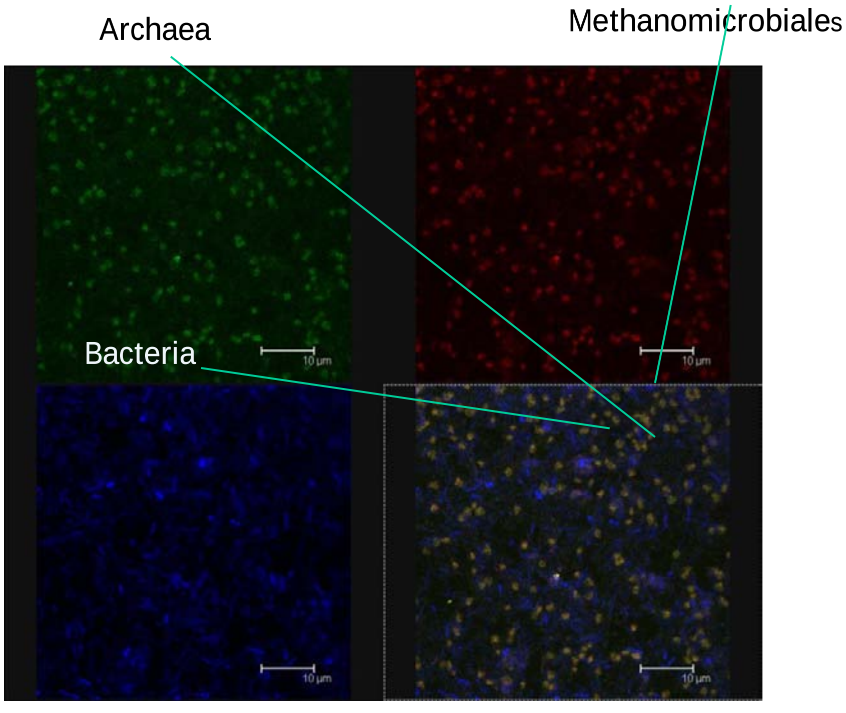




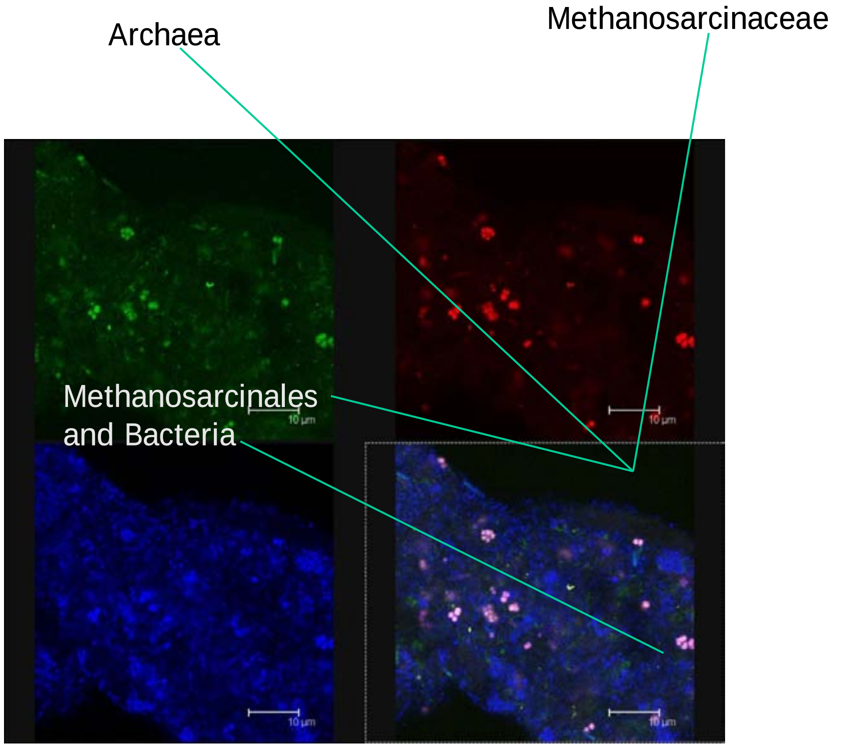
Classification of Methanogens

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

Conclusions

Trace elements

- Selenium and cobalt are the key trace elements needed for the long-term stability of food waste digesters, but are likely to be lacking in the food waste;
- The minimum concentrations recommended in food waste digesters for selenium, cobalt are around 0.16, 0.22 mg l^{-1} respectively, when running at a moderate organic loading rate;
- A total selenium concentration greater than 1.5 mg l^{-1} is likely to be toxic to the microbial consortium in the digester;
- Food waste is likely to have sufficient Al, B, Cu, Fe, Mn, and Zn. We are still not sure about Ni, Mo and W

Digester operation

- Following proper trace element supplementation strategy, food waste digesters can be operated stably with low VFA concentrations at an organic loading rate of 5 kg VS m^{-3} d^{-1} with a volumetric biogas production of 3.8 STP m^3 m^{-3} d^{-1} and specific biogas production of 0.76 STP m^3 kg^{-1} VS

- 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.

Thank you