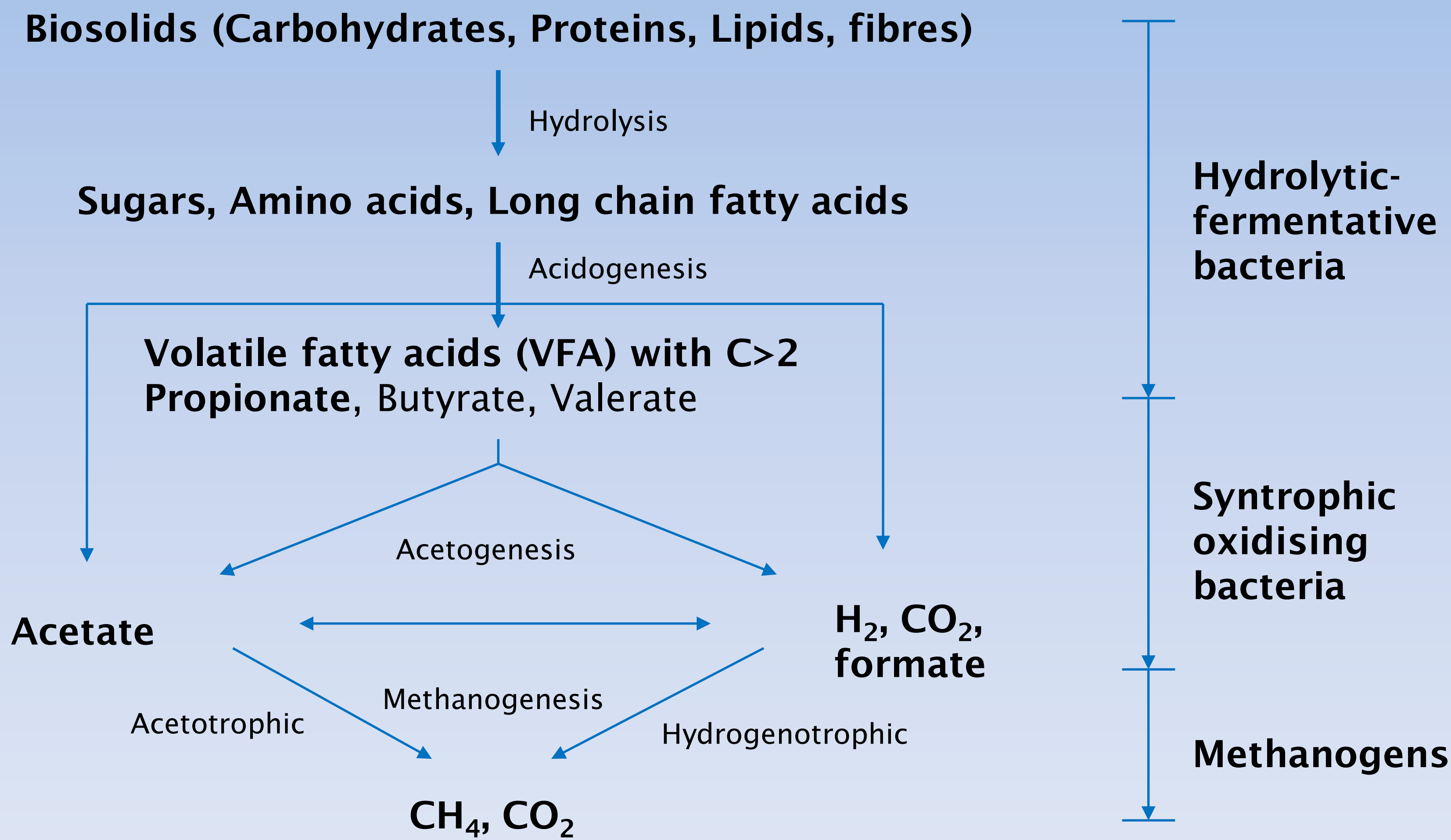
Anaerobic digestion of food waste

Supporting Research

Dr Yue Zhang

Anaerobic conversion of biomass to CH_4

Strict syntrophic manner



Anaerobic digestion operation

Input → **AD process** → **Output**

Input

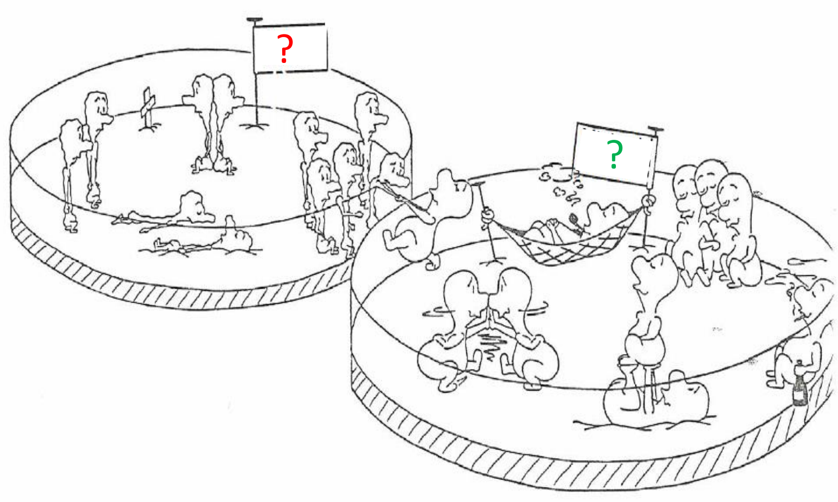
- Calorific value
- Biochemical composition
- Elemental composition
- Chemical oxygen demand
- Biodegradable carbon : TKN
- Macro-nutrients
- Essential trace elements
- Potentially toxic elements
- etc

AD process

- *Temperature*
- *Hydraulic retention time*
- *Solid retention time*
- *Flow mode*
- *Feeding regime*
- *Low solids, high solids*
- *One stage, two stage*
- *etc*

Output

- Optimised Biogas production
- Stabilised and useful digestate

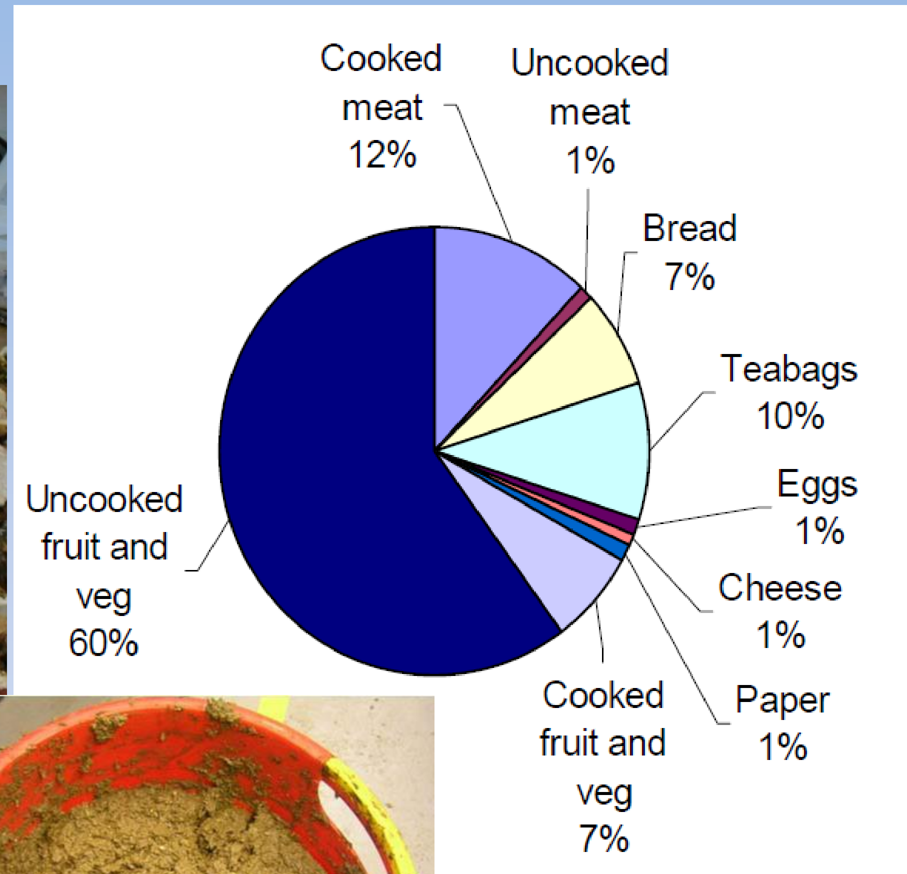


Cartoons from: What's so funny about microbiology? by Joachim Czichos

Why separated 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 AD process simple

Collected food waste



Laboratory digesters for food waste trials

CSTR-type digesters:

2-litre

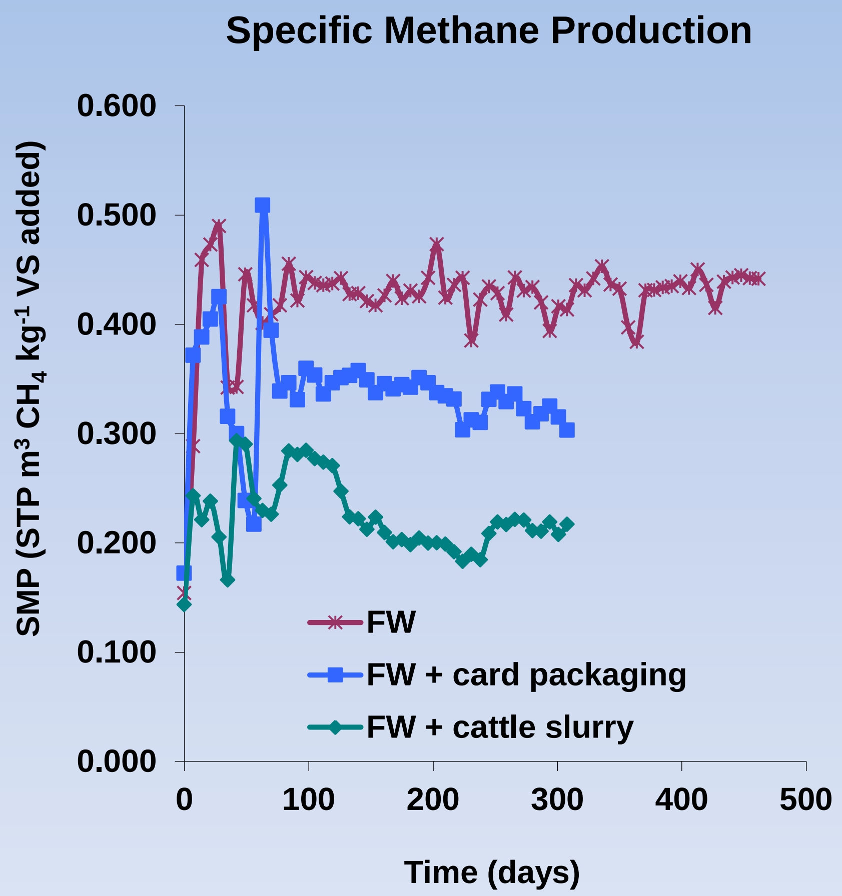
5-litre

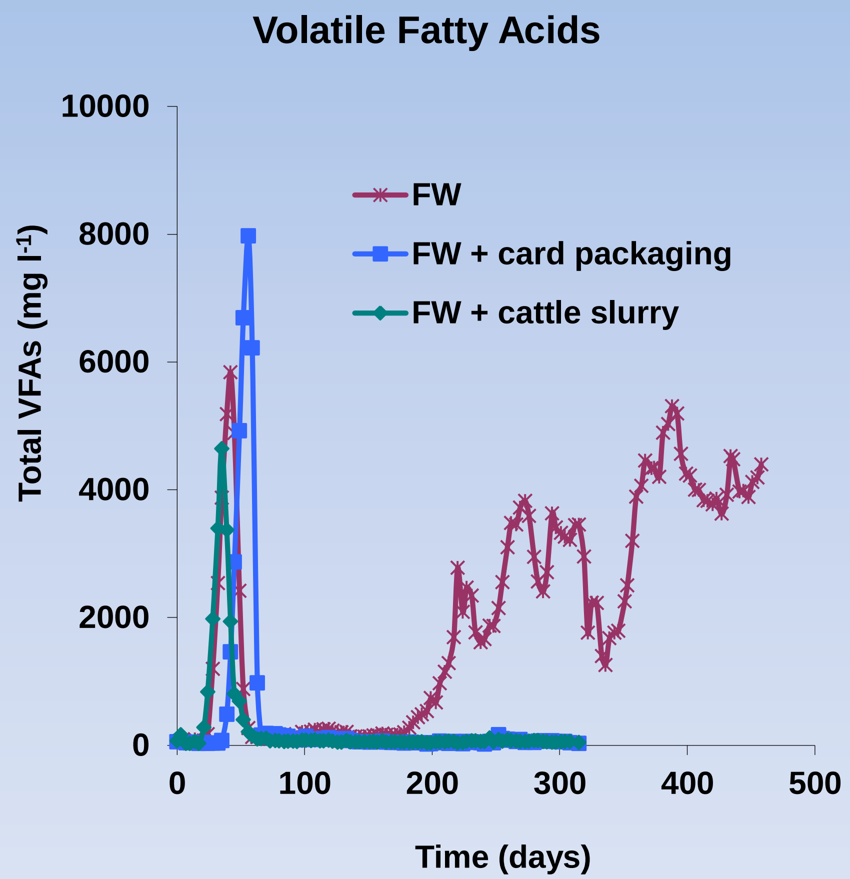
40-litre

100-litre

Mesophilic food waste digestion performance

Inoculum: sewage sludge digestate; **Temperature:** 36±1° C; **Organic loading rate:** 2 kg VS m-3 d-1





Long chain fatty acids (LCFA) accumulation

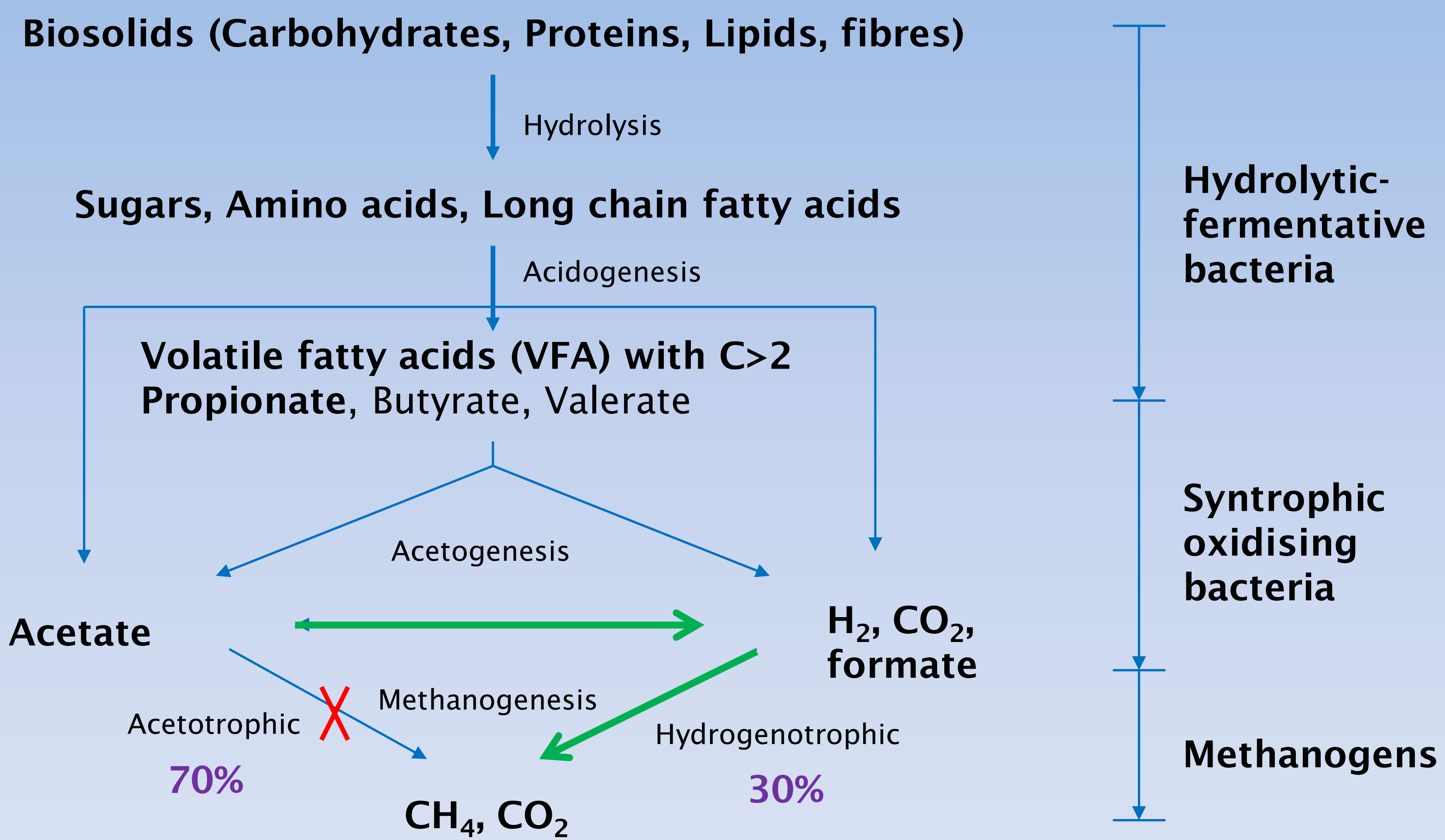
X-ray diffraction analysis

Instability issue of food waste digestion

- **Negative response**
  - **accumulation of long chain and volatile fatty acids**
- **Loading limit**
  - **less than 2 kg VS m^{-3} day^{-1}**

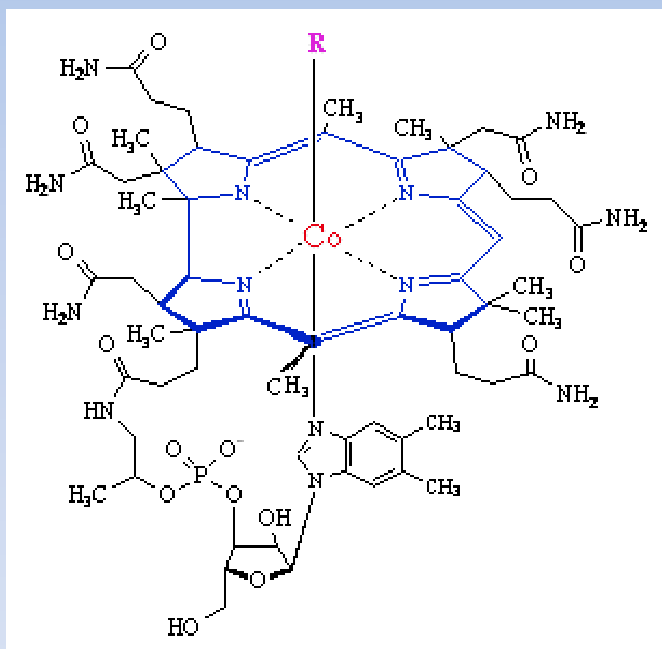
Sub-healthy

Anaerobic conversion of food waste to CH_4

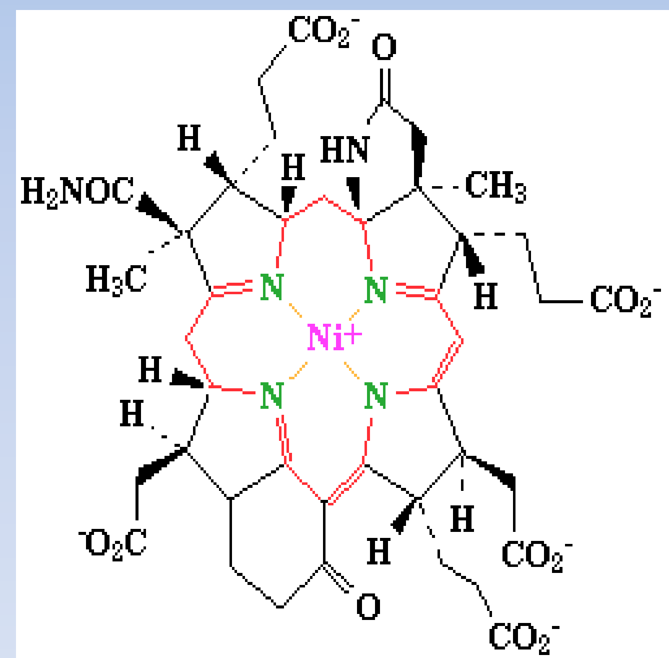


Function of trace elements in AD

- **Active centre of enzymes and electron carrier molecules**
- **Trace elements:** Co, Ni, Fe, Se, Mo, W, Zn, Cu, Mn, Al, B



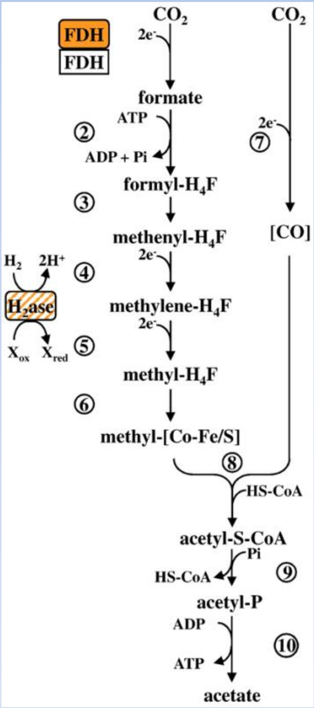
Corrinoid



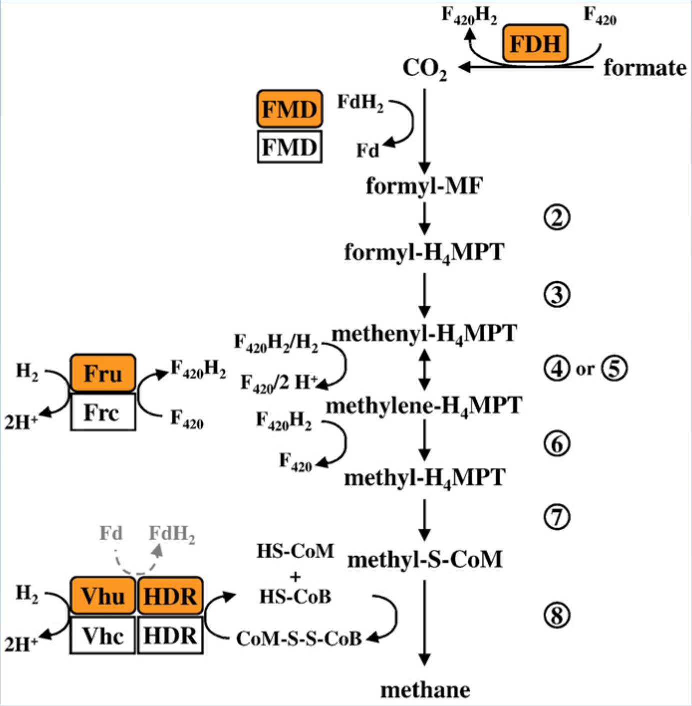
Cofactor F430

Function of trace elements in food waste AD

- **Active centre of enzymes and electron carrier molecules**
- **<u>Ammonia toxicity</u>:** 4000~7000 mg N l^{-1}
- **Trace elements deficiency:** Co, Ni, Fe, Se, Mo, W, Zn, Cu, Mn, Al, B



The reductive Wood-Ljungdahl pathway of acetogenesis



The path of CO2 reduction to methane in *Methanococcus* species

Reference: Stock T. and Rother M. (2009) Selenoproteins in Archaea and Gram-positive bacteria. Biochimica et Biophysica Acta 1790, 1520-1532.

Note: selenoproteins involved are round-boxed in orange, and the potential involvement of a Sec-containing hydrogenase is indicated by the dashed round box.

Stable performance of food waste digestion
- Trace element supplementation research

Aim - Optimising trace element supplementation strategy

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

Research approaches

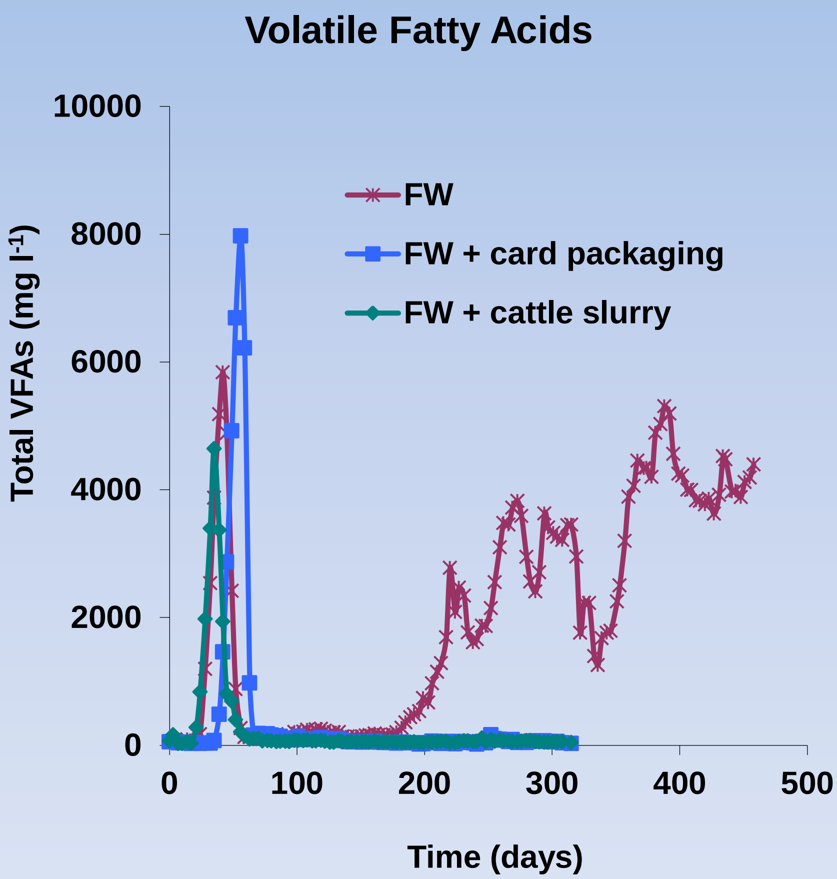
- Batch flask trials for screening purpose
- Semi-continuous digester operation to monitor the long-term effect

Key monitoring parameters

- Trace elements (TE) concentrations
- Volatile fatty acids (VFA) concentrations

Batch screening tests

Food waste digestate used



Food waste digestate parameters	
pH	8.0
Total ammonium nitrogen (mg-N l^{-1})	4700
Total volatile fatty acid (mg l^{-1})	4400
Acetic acid (mg l^{-1})	4100
Propionic acid (mg l^{-1})	100

Substrate pike	Concentration (mg l^{-1})
Sodium acetate	4500 as acetic acid
Sodium propionate	8000 as propionic acid
Glucose	4000
Starch	4000

Fractional factorial design

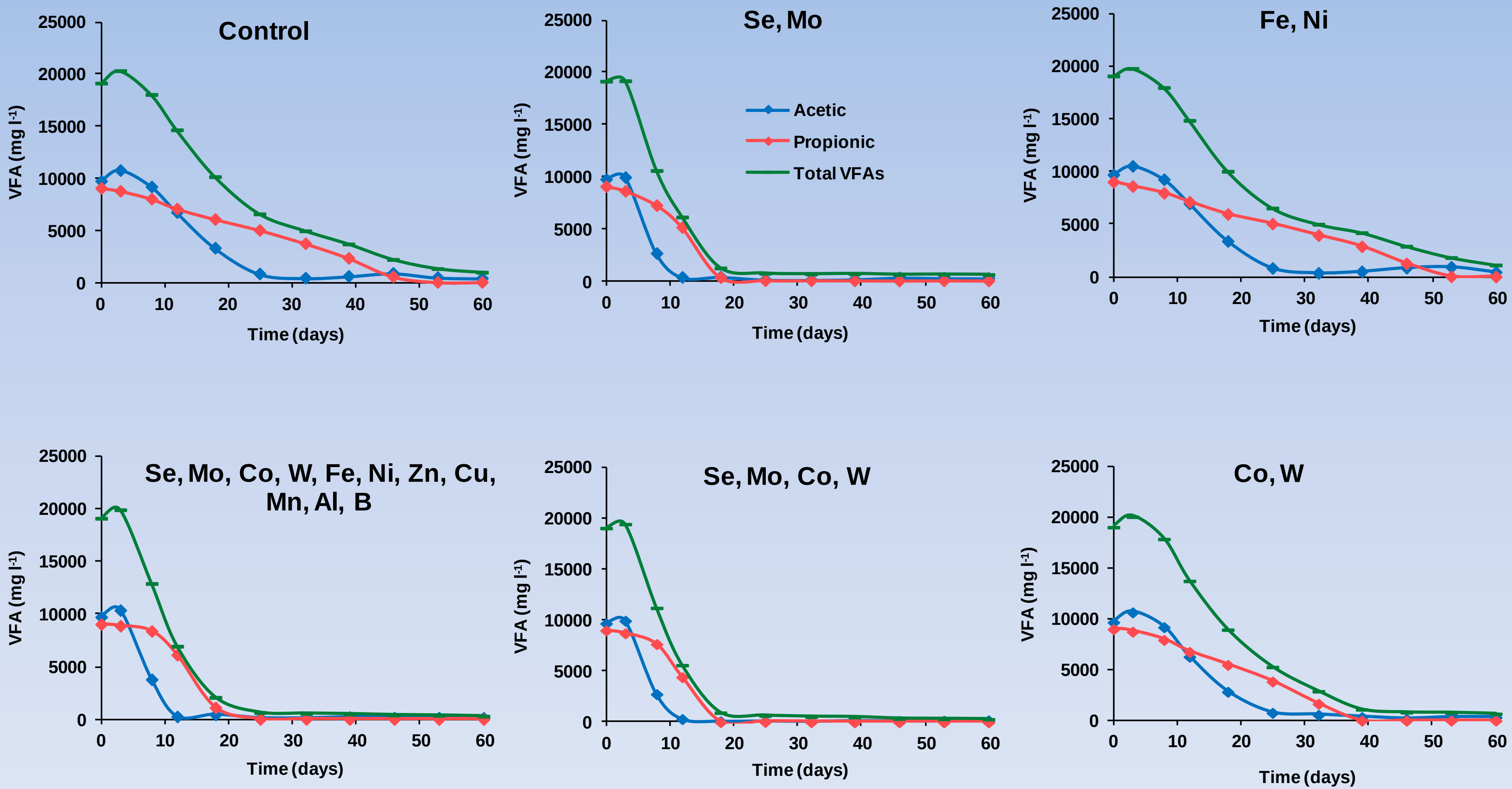
Run	Pattern	Co	Ni	Mo	Se	Fe	W	Zn	Cu	Mn	Al	B
1	–––––––––––	-	-	-	-	-	-	-	-	-	-	-
2	–––+++–––––	-	-	-	Se	Fe	W	-	-	-	-	-
3	––+–++–––––	-	-	Mo	-	Fe	W	-	-	-	-	-
4	––++–––––––	-	-	Mo	Se	-	-	-	-	-	-	-
5	–+––+––––––	-	Ni	-	-	Fe	-	-	-	-	-	-
6	–+–+–+–––––	-	Ni	-	Se	-	W	-	-	-	-	-
7	–++––+–––––	-	Ni	Mo	-	-	W	-	-	-	-	-
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

Trace element concentrations spiked

Essential element	Compound used	Trace element concentration (mg l^{-1})	
		Supplemented at the beginning of the tests	Existing in the test digestate
Cobalt (Co)	$CoCl_2{\cdot}6H_2O$	1.0	0.083
Nickel (Ni)	$NiCl_2{\cdot}6H_2O$	1.0	2.9
Molybdenum (Mo)	$(NH_4)_6Mo_7O_{24}{\cdot}4H_2O$	0.2	0.29
Selenium (Se)	Na_2SeO_3	0.2	0.050
Tungsten (W)	$Na_2WO_4{\cdot}2H_2O$	0.2	<0.035
Iron (Fe)	$FeCl_2{\cdot}4H_2O$	5.0	173.7
Zinc (Zn)	$ZnCl_2$	0.2	8.11
Copper (Cu)	$CuCl_2{\cdot}2H_2O$	0.1	5.75
Manganese (Mn)	$MnCl_2{\cdot}4H_2O$	1.0	18.5
Aluminium (Al)	$AlCl_3{\cdot}6H_2O$	0.1	63.3
Boron (B)	H_3BO_3	0.1	2.5

Experimental set up

Volatile fatty acids degradation profiles



Statistical analysis
- TE on acetic acid degradation

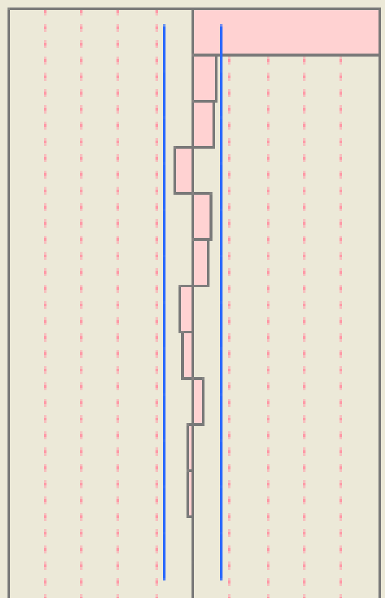
Effect of trace elements on acetic acid degradation

HAc- Fit Least Squares

Response Rate

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Se	369.125	13.05667	28.27	0.0012*
Mo	44.75	13.05667	3.43	0.0756
Co*W	40.375	13.05667	3.09	0.0906
Co*Se	-34.625	13.05667	-2.65	0.1176
Co*Mo	34.25	13.05667	2.62	0.1198
W	33.375	13.05667	2.56	0.1250
Co	-24.25	13.05667	-1.86	0.2044
Ni*Se	-18.625	13.05667	-1.43	0.2898
Co*Ni	18.5	13.05667	1.42	0.2922
Ni*Mo	-11	13.05667	-0.84	0.4882
Fe	-8.625	13.05667	-0.66	0.5768
Ni	-2.5	13.05667	-0.19	0.8658
Co*Fe	-1.875	13.05667	-0.14	0.8990



Statistical analysis
- TE on propionic acid degradation

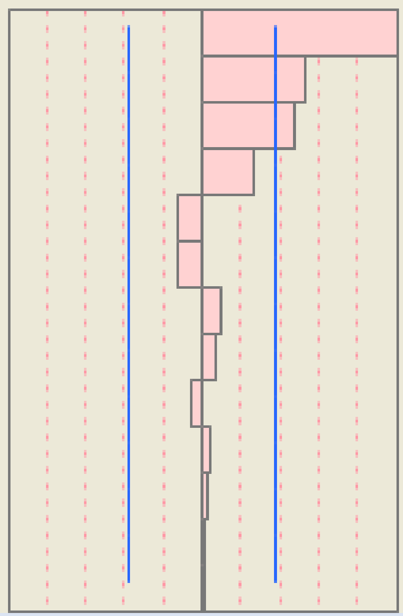
Effect of trace elements on propionic acid degradation

HPr- Fit Least Squares

Response Rate

Sorted Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Se	171.625	15.09993	11.37	0.0077*
Mo	91.25	15.09993	6.04	0.0263*
Co*W	81.5	15.09993	5.40	0.0327*
Co	45.75	15.09993	3.03	0.0939
Ni	-20.75	15.09993	-1.37	0.3031
Co*Se	-20.75	15.09993	-1.37	0.3031
Co*Fe	16.5	15.09993	1.09	0.3886
Co*Ni	11.625	15.09993	0.77	0.5219
Ni*Se	-8.5	15.09993	-0.56	0.6302
Co*Mo	6.375	15.09993	0.42	0.7139
Ni*Mo	4.875	15.09993	0.32	0.7774
Fe	2.625	15.09993	0.17	0.8780
W	1.875	15.09993	0.12	0.9125



Batch experiments - result

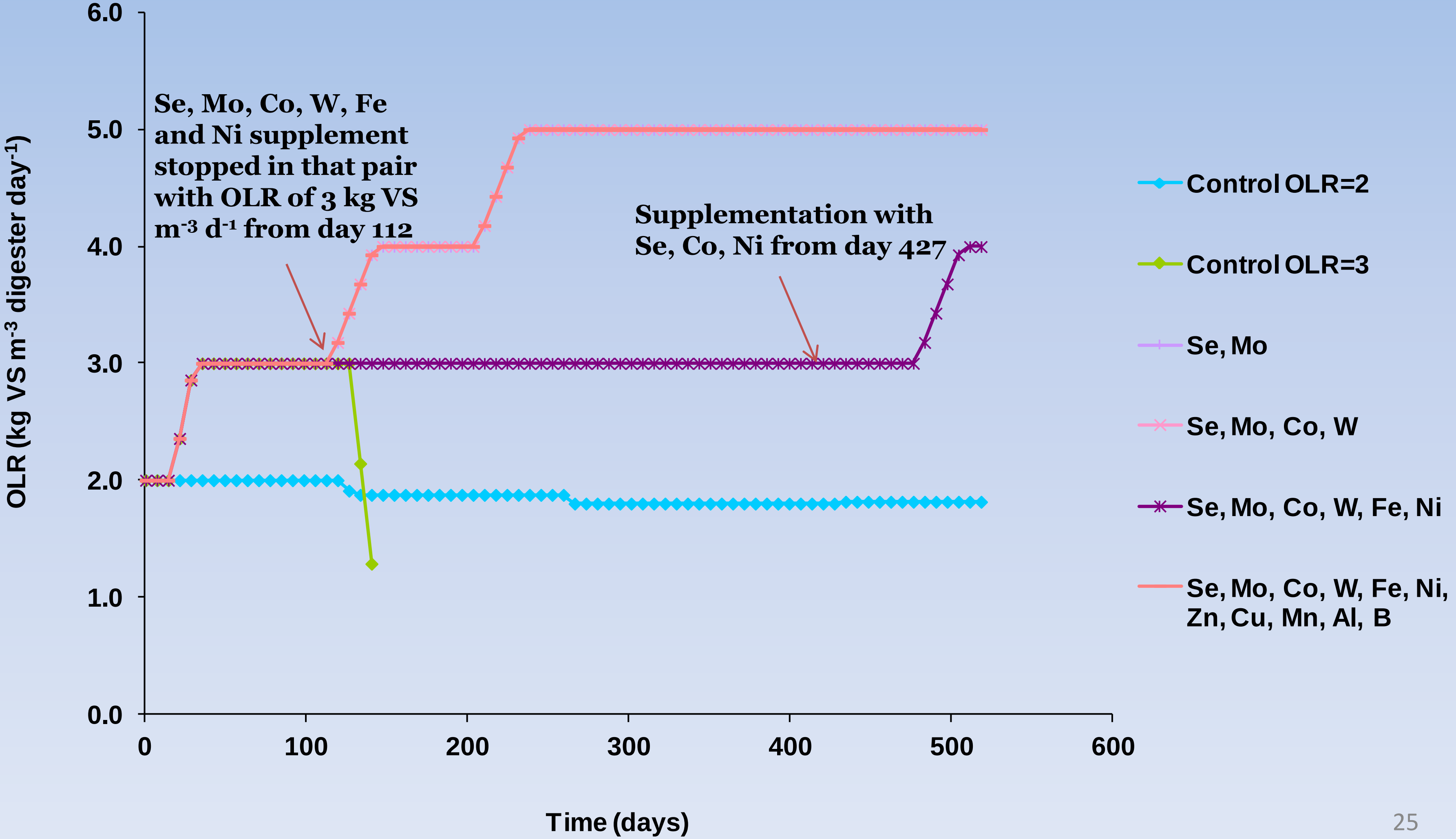
Essential trace element for acetic and propionic acid degradation in food waste digestate

Tier	Trace element	Compound		Dosing strength (g $tonne^{-1}$)
1st	Selenium (Se)		Na_2SeO_3	0.2
	Molybdenum (Mo)		$(NH_4)_6Mo_7O_{24}\cdot 4H_2O$	0.2
2nd	Cobalt (Co)		$CoCl_2\cdot 6H_2O$	1.0
	Tungsten (W)		$Na_2WO_4\cdot 2H_2O$	0.2
3rd	Iron (Fe)		$FeCl_2\cdot 4H_2O$	5.0
	Nickel (Ni)		$NiCl_2\cdot 6H_2O$	1.0
4th	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

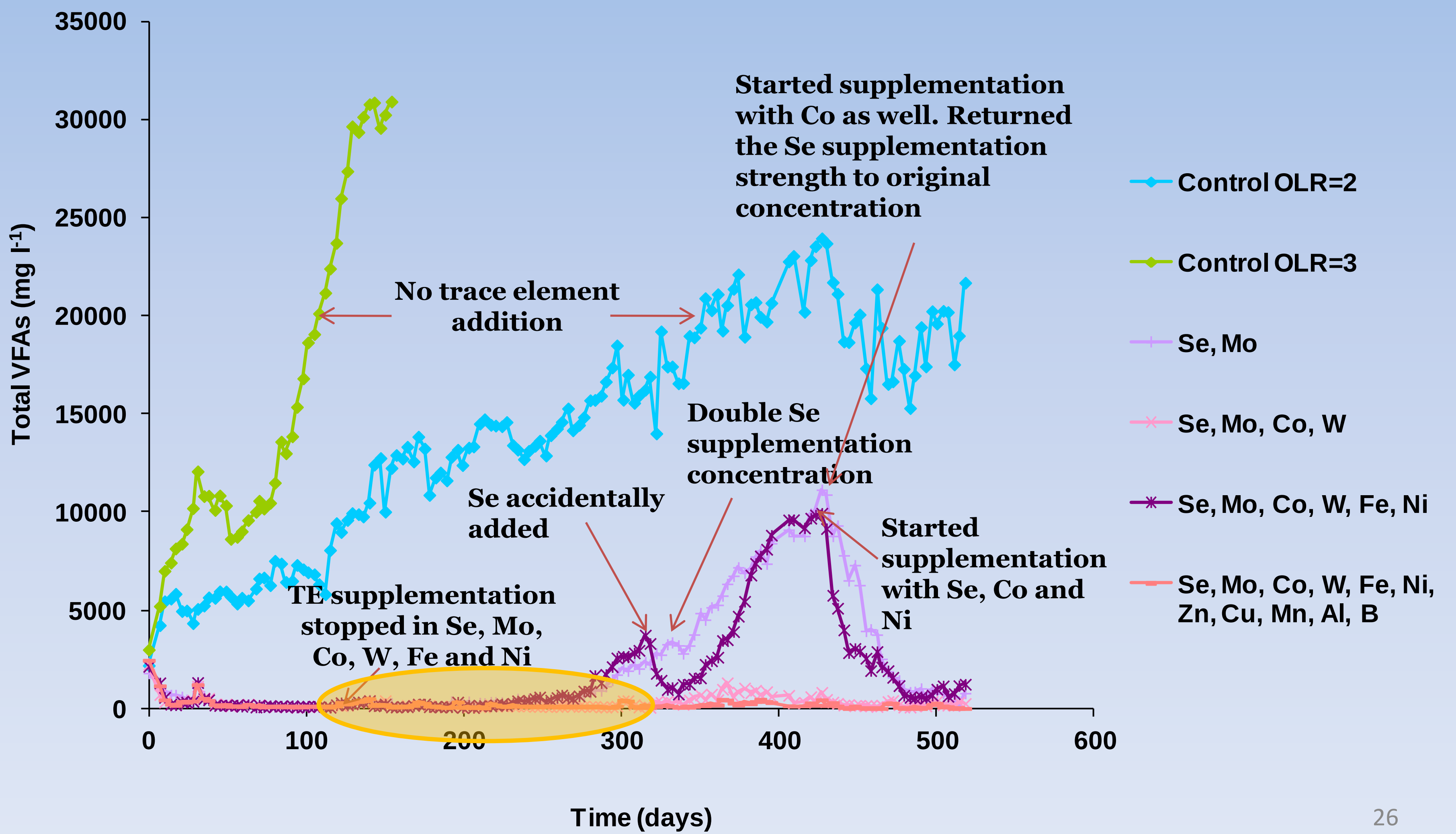
Semi-continuous trials

Digesters

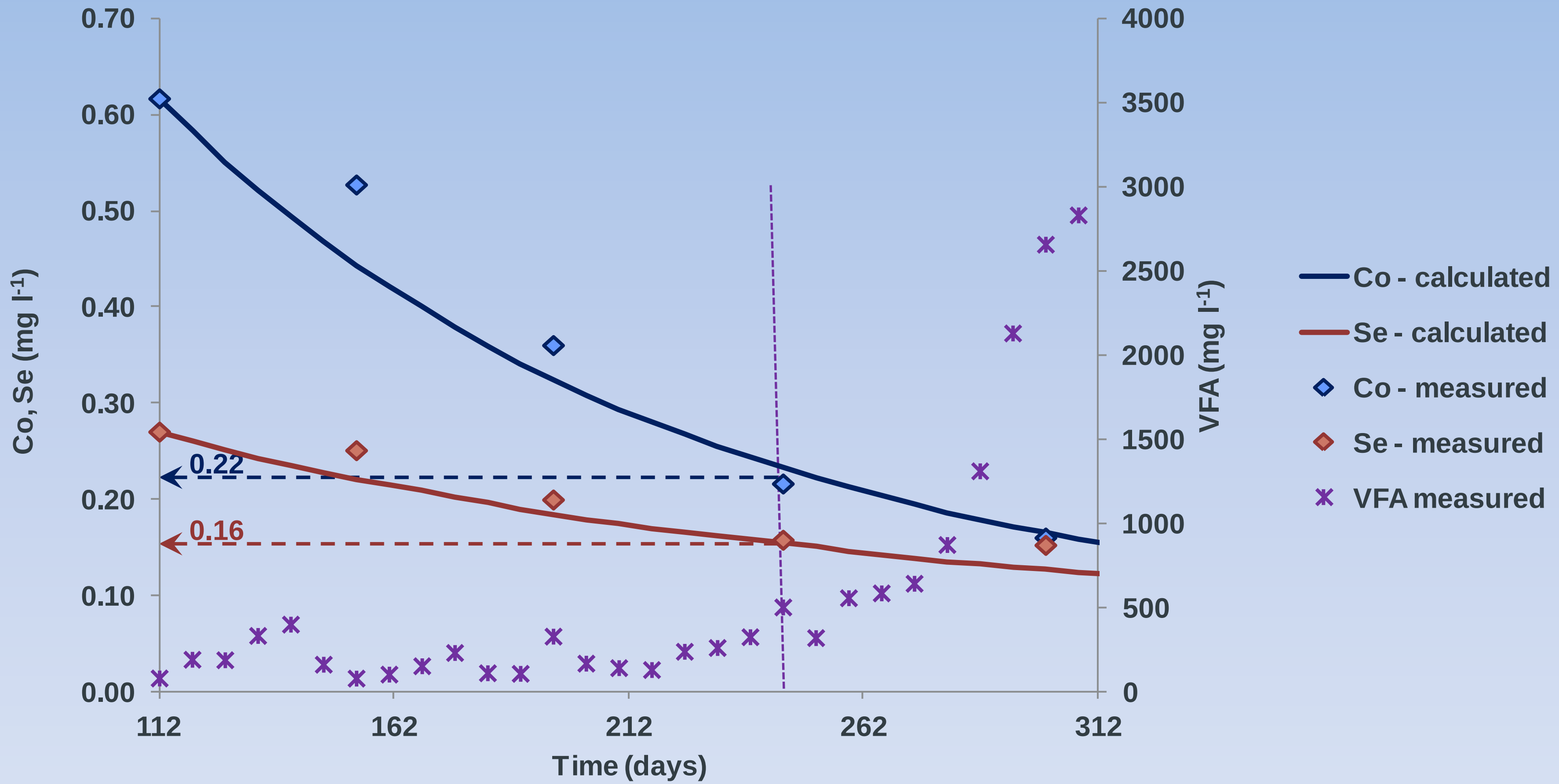
Organic loading rate (OLR)



Volatile fatty acids (VFA) profile



Co and Se dilute-out curves *vs* VFA profile



Se: 0.16 mg l^{-1} = 0.16 g m^{-3} = 10^{21} Se m^{-3}

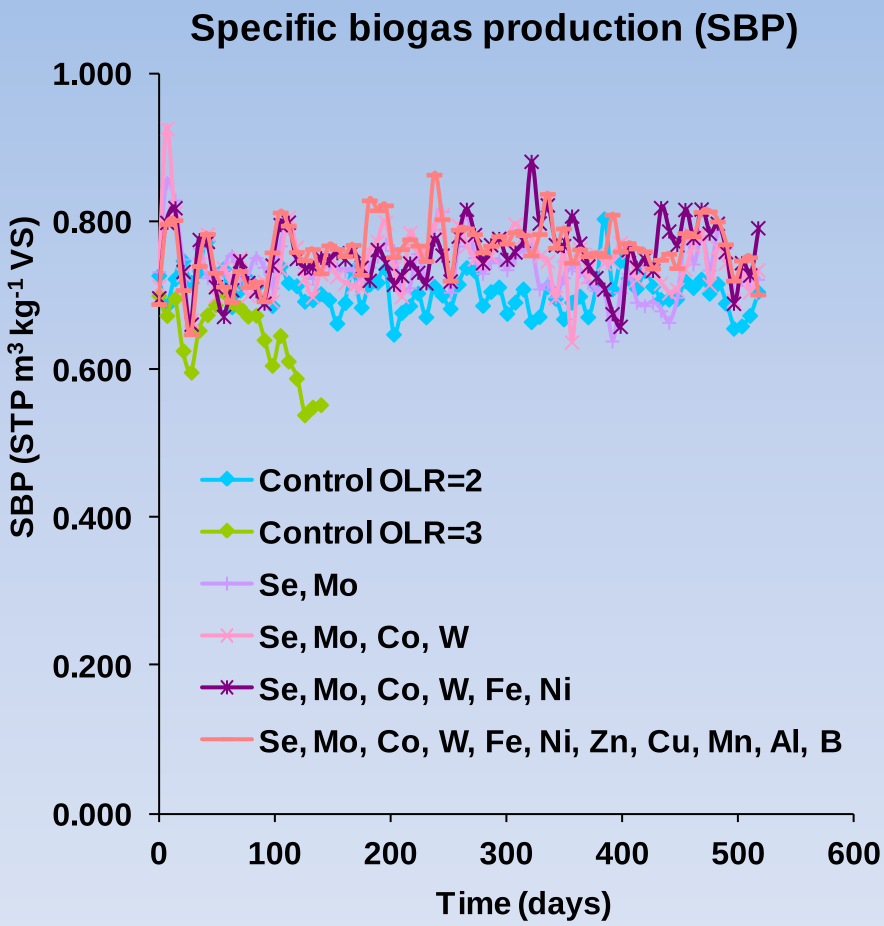
Microorganisms: 10^{16} m^{-3}

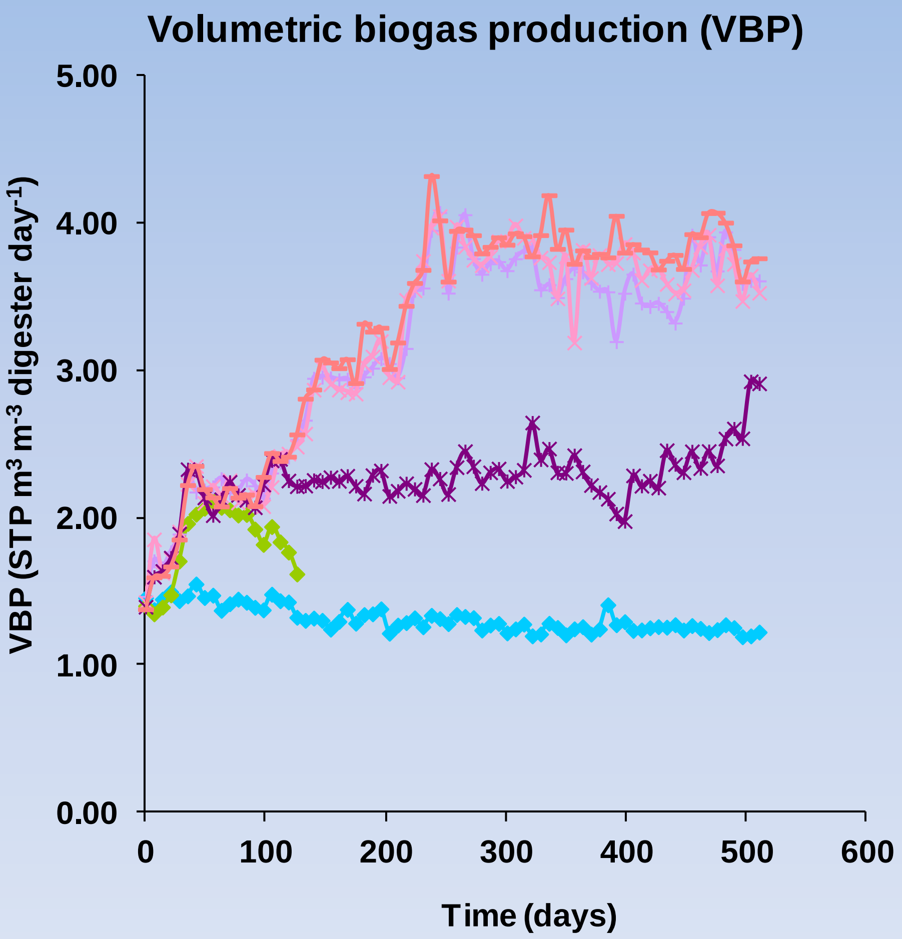
TE required *vs* TE in the UK food waste

	Minimum requirement at a moderate loading rate	Hackney, London	Eastleigh, Hampshire	Luton, South Bedfordshire	Ludlow, Shropshire
Cobalt (Co)	**0.22**	**0.09** ± 0.05	**0.02** ± 0.01	**0.02** ± 0.00	**< 0.06**
Selenium (Se)	**0.16**	**0.10** ± 0.08	**0.03** ± 0.00	**0.28** ± 0.14	**< 0.07**
Total Kjeldahl Nitrogen (TKN)		8100	7500	7400	8100

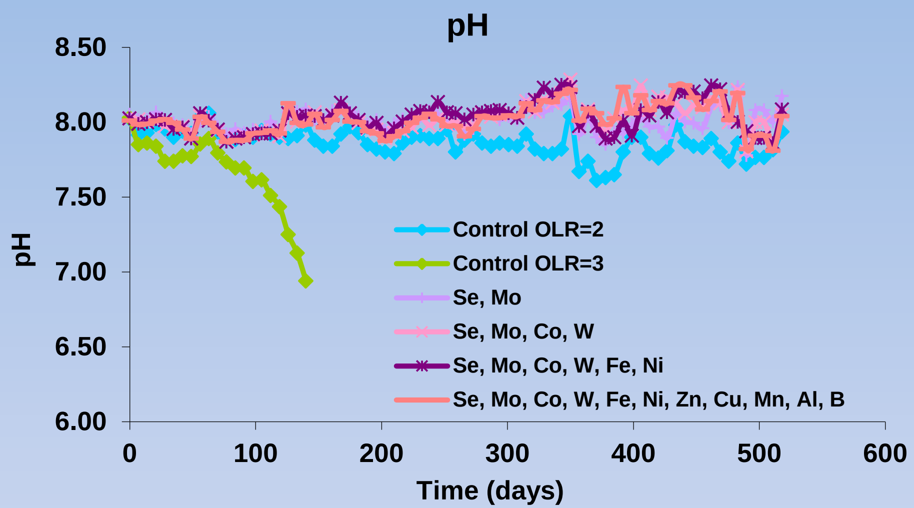
Unit: mg kg^{-1} fresh matter

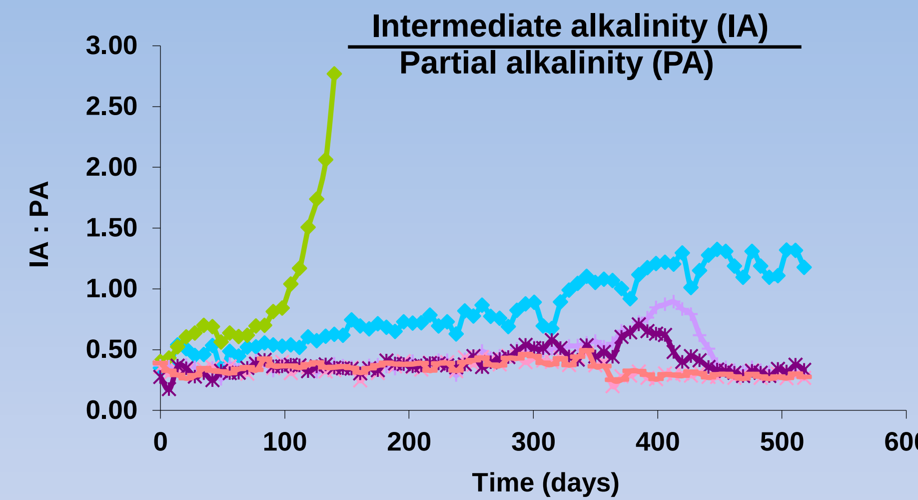
Digestion efficiency

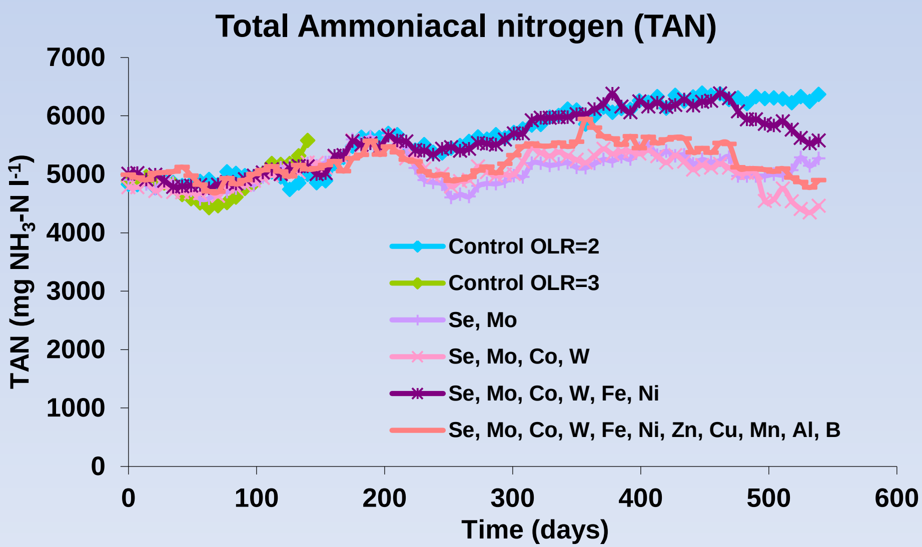


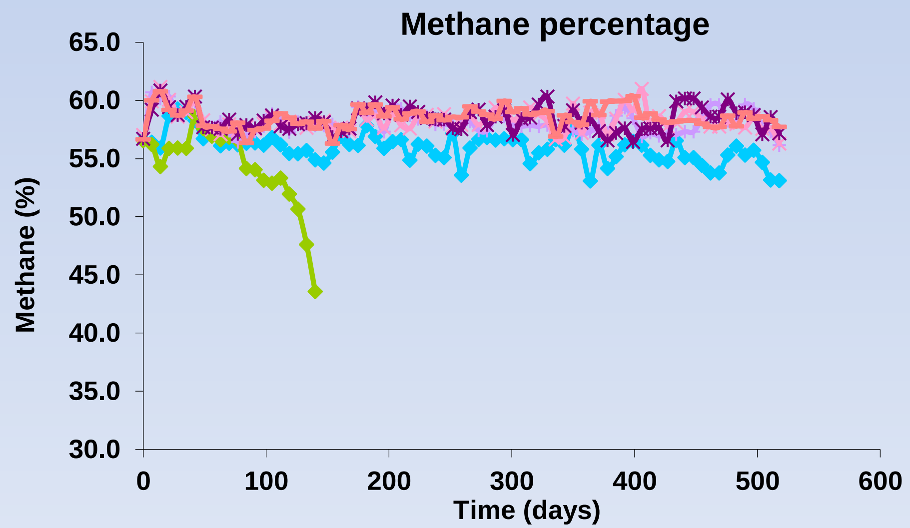


Other digester parameters

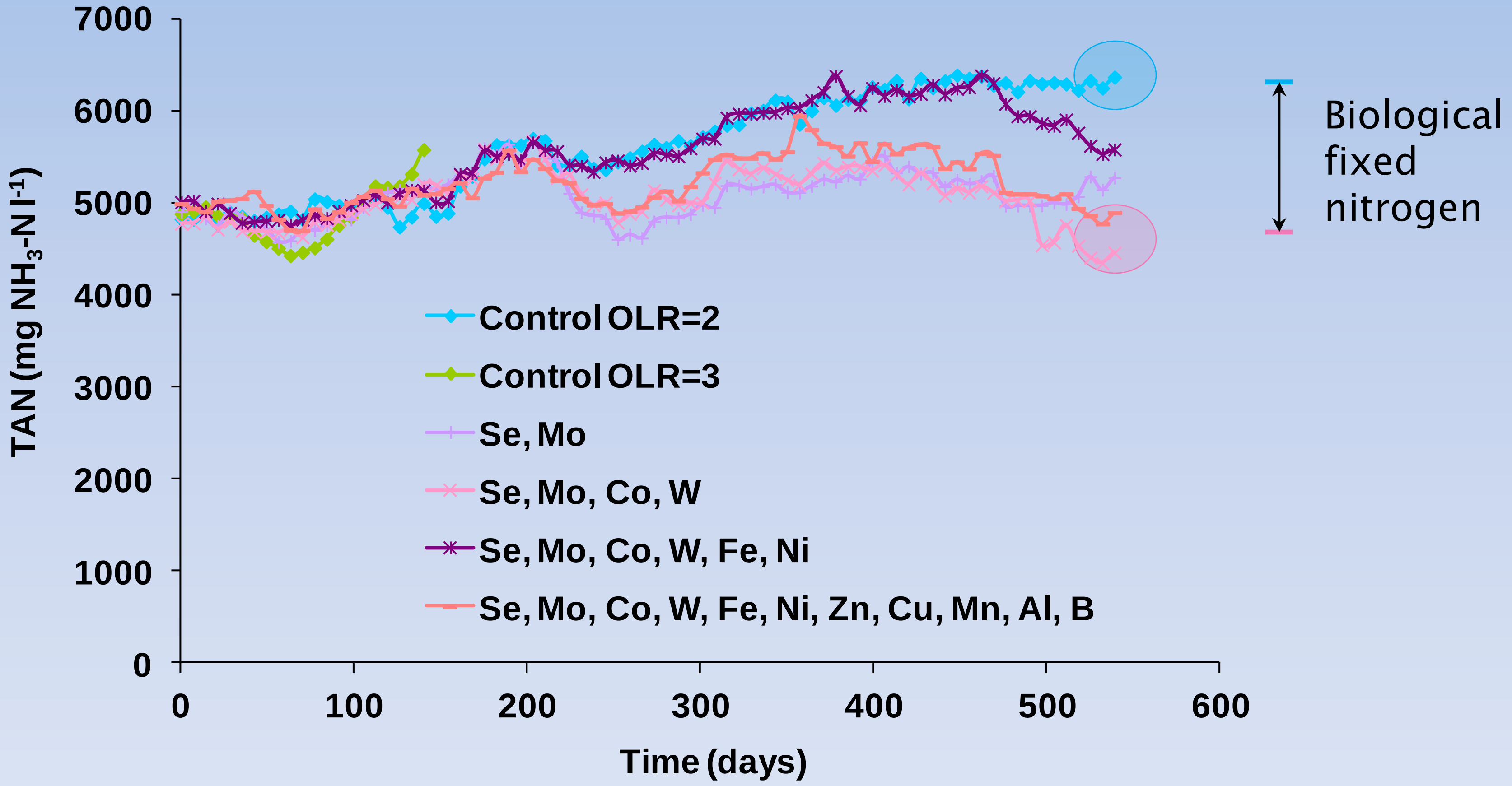








Total ammoniacal nitrogen (TAN)



FISH analysis on methanogenic community structure

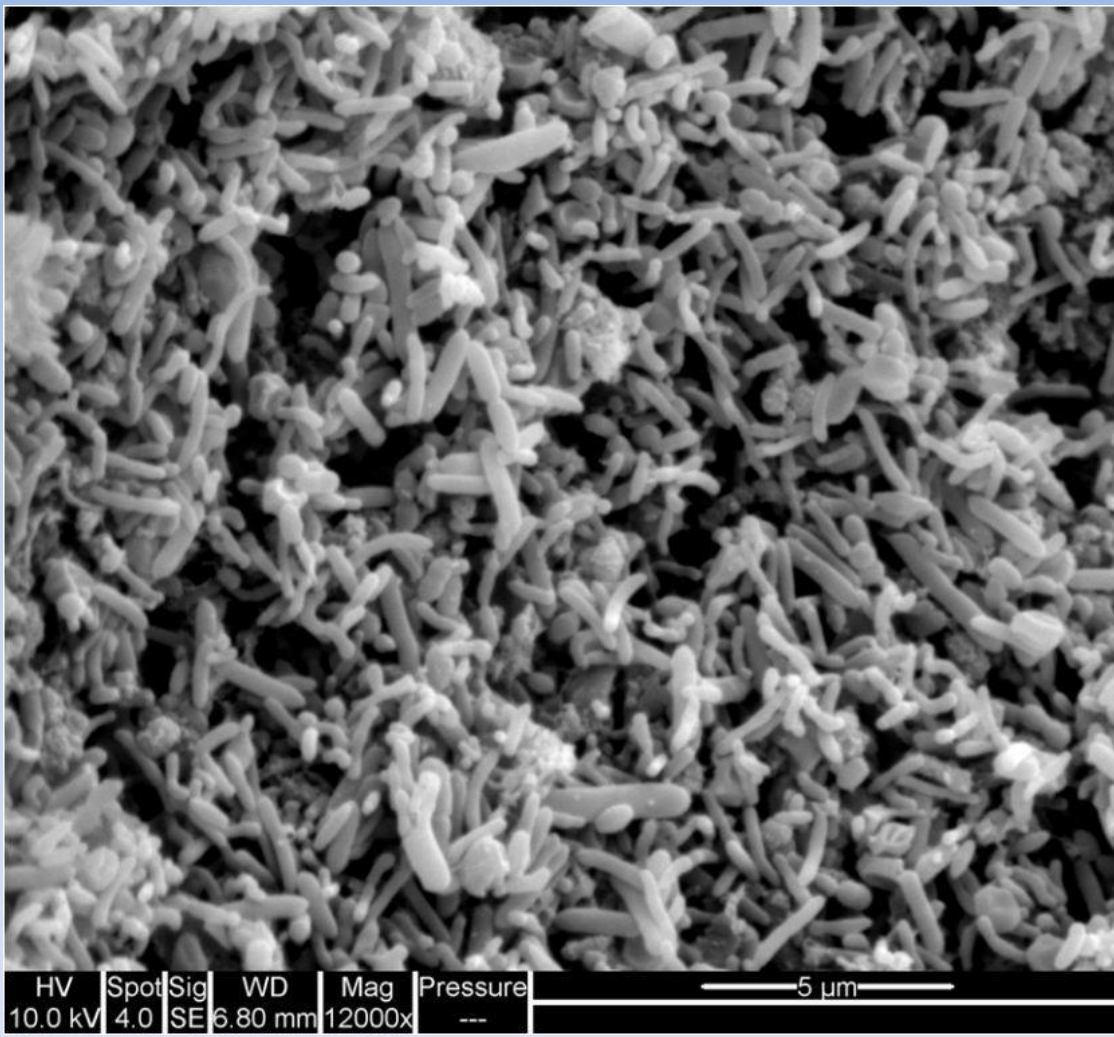
Classification of Methanogens

Methanogen	**Carbon source**
Methanobacteriales	CO_2 / formate
Methanococcales	CO_2 / formate
Methanomicrobiales	CO_2 / formate
Methanosarcinales *Methanosarcinaceae*	CO_2 Acetate
Methanosarcinales *Methanosaetaceae*	Acetate

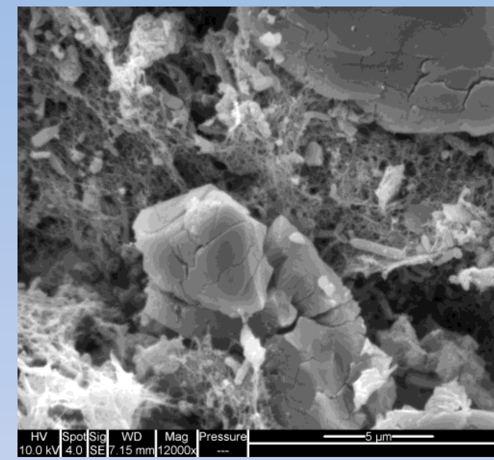
Hydrogenotrophic

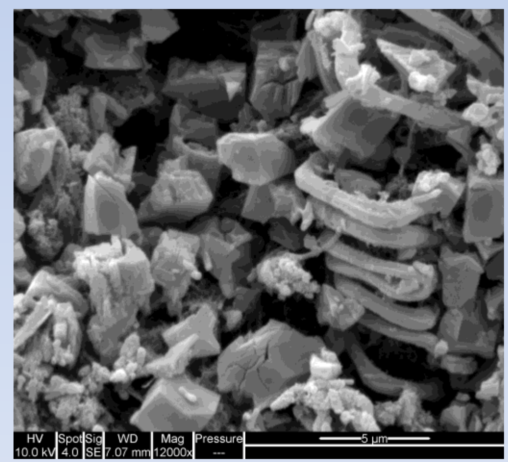
Acetotrophic

SEM images after density gradient centrifugation



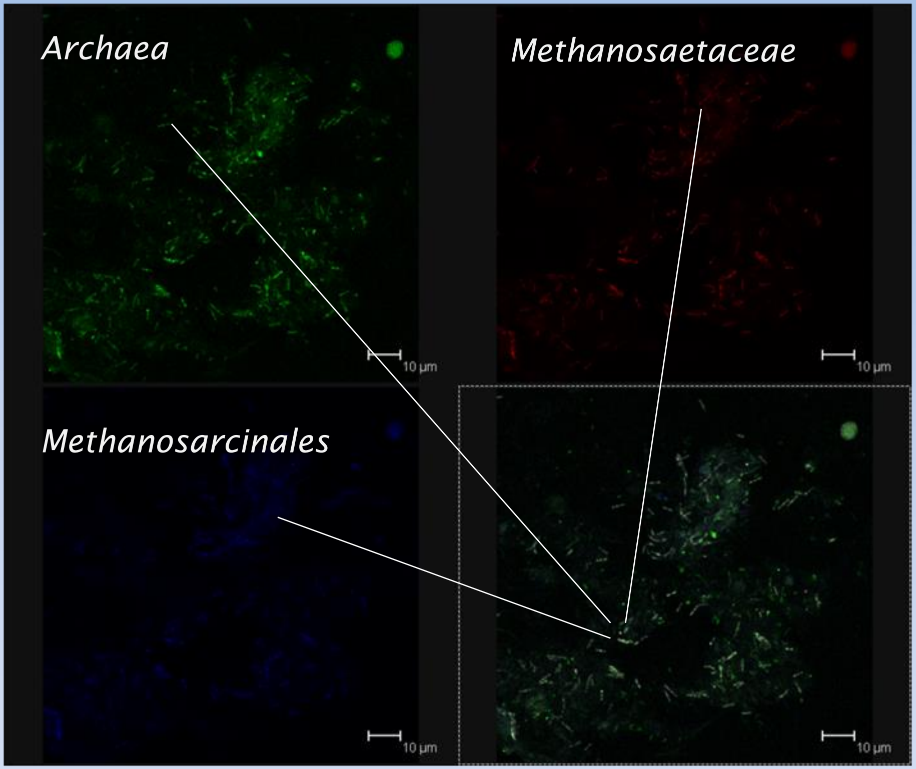
Separated microbial biomass





Food waste residues

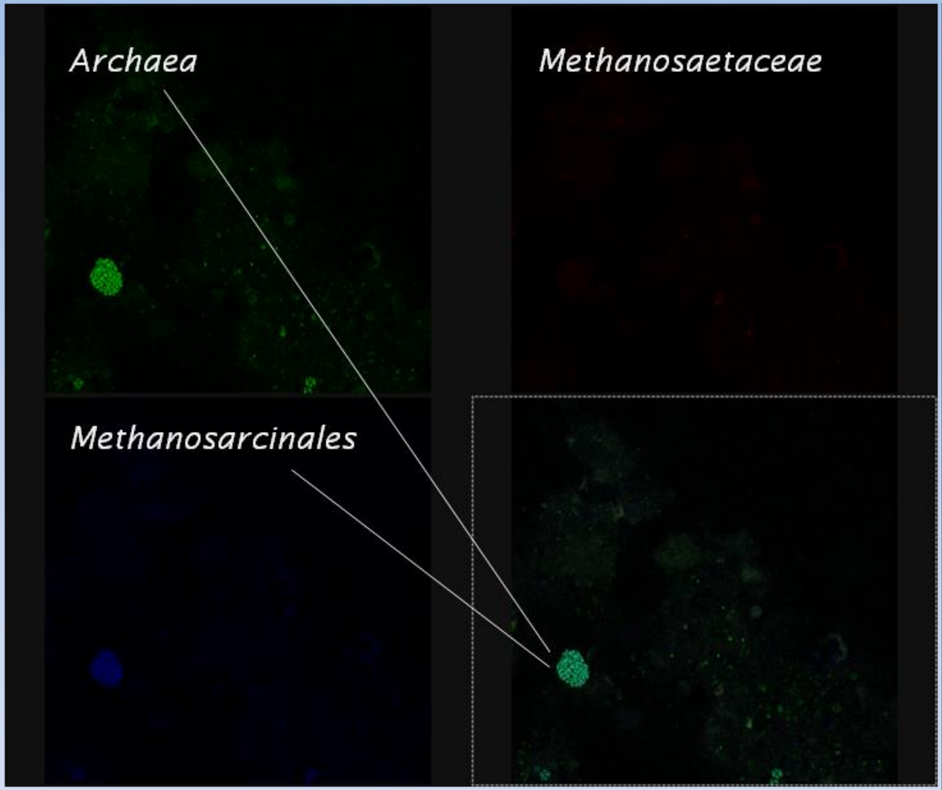
Fluorescence in-situ hybridisation (FISH)



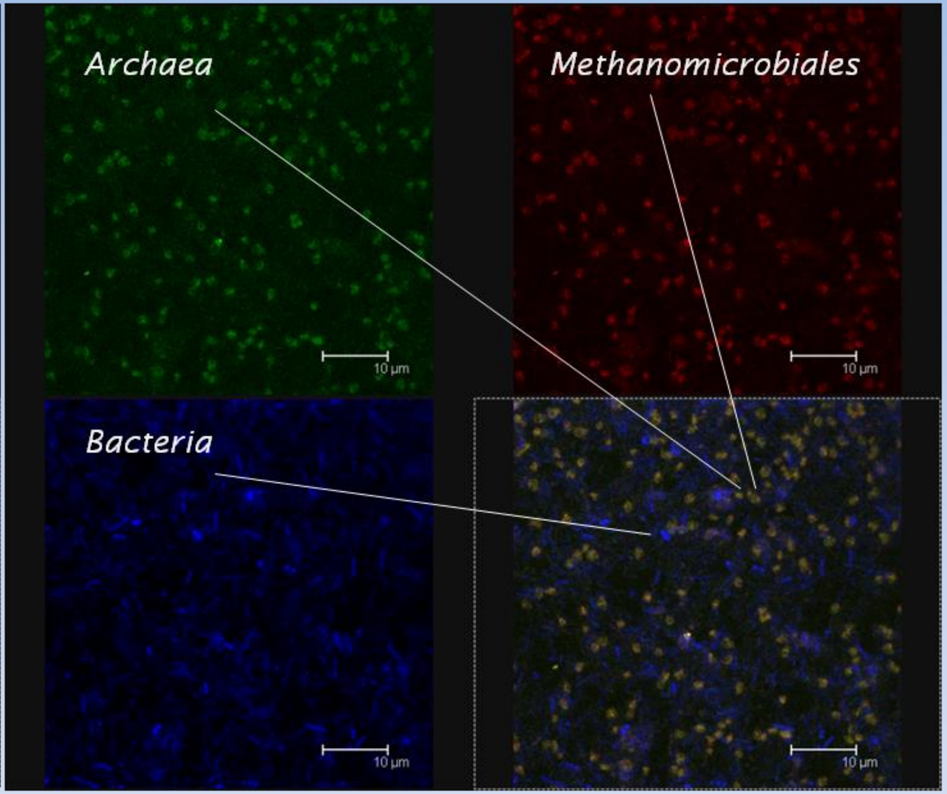
Inoculum – a wide range of methanogens

Probe name	Target group	Fluoro-chrome	Formamide (%)
EUB338	*Bacteria (most)*	Cy5	20~50
EUB338+	*Bacteria (remaining)*	Cy5	20~50
ARC915	*Archaea*	6-Fam	20~50
MX825	*Methanosaetaceae*	Cy3	50
MS1414	*Methanosarcinaceae*	Cy3	50
hMS1395	MS1414-helper	-	50
hMS1480	MS1414-helper	-	50
MSMX860	*Methanosarcinales*	Cy5	45
MG1200	*Methanomicrobiales*	Cy3	20
MB1174	*Methanobacteriales*	Cy3	45
MC1109	*Methanococcales*	Cy3	45

Fluorescence in-situ hybridisation (FISH)

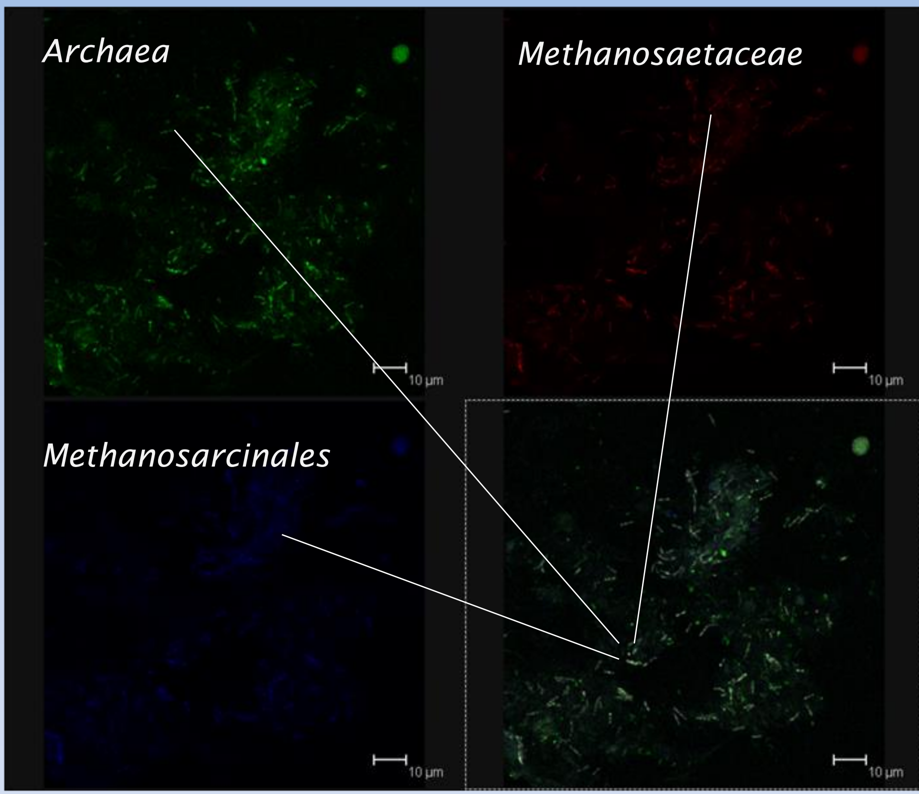


After 3 months

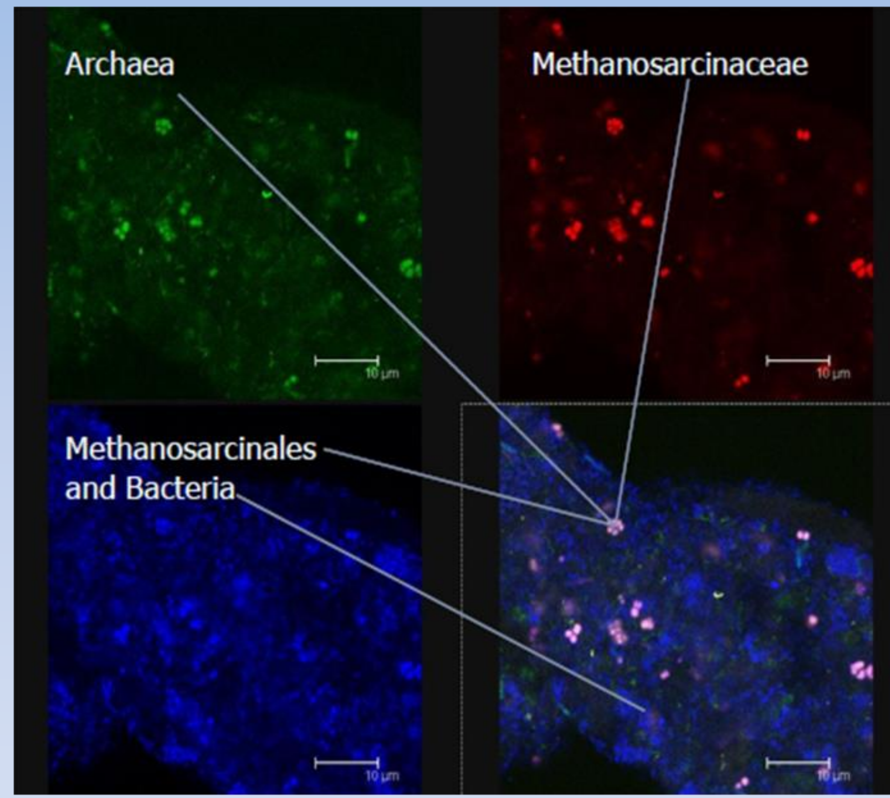


After 1.5 years

FISH images on another digestate sample



Inoculum



Vegetable waste digestate

Conclusions

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

Conclusions – 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 7 kg VS m^{-3} d^{-1} with a volumetric methane production of > 3.0 STP m^3 m^{-3} d^{-1} and specific methane production of ~ 0.45 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

Further consideration

- The concept of the use of essential trace elements has been accepted by AD operators
- The species and quantity of trace elements supplemented are often determined by experiments or trial-and-error approach
- Lack of insight knowledge on the impact of trace elements in AD under different process conditions
- The fate of trace elements (heavy metals, selenium) once they leave the digesters
- COST Action: European network on ecological functions of trace metals in anaerobic biotechnologies

Anaerobic digestion challenges

Expectation on anaerobic digestion

- Robust
- Efficient
- Flexible

Future research needs

- Have insight into the microbial activities
- Better control and diagnose the digestion system
- Improve the conversion efficiency of organic materials