Co-digestion of Food Waste with Sewage Sludge

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民以食為天 《漢書·酈食其傳》

Bread is the staff of life

Food waste in the world and its impacts

1.3 billion tones (one third of the food produced) food are lost and wasted per year globally during the production, retail and consumption stages, averagely **0.5 kg per capita per day** (UNEP, 2013).

Moralists ask why some people waste food when others are hungry.

Economists point out that it causes a major waste of resources, including water, land, energy, labor and capital.

As *environmental engineers*, we concern that food waste

- leads to wasteful use of chemicals, such as fertilizers and pesticides;
- produces greenhouse gas emissions, contributing to global warming and climate change since vast amount of food waste goes to landfills, just like what is happening at Hong Kong.

http://www.unep.org/wed/2013/quickfacts/

Food waste at Hong Kong and possible solutions

- 3584 tones Food Waste per day (0.5 kg per capita per day) are being disposed at landfill sites of Hong Kong (EPD, 2012), as the largest category (36%) of the solid waste sent to landfill.

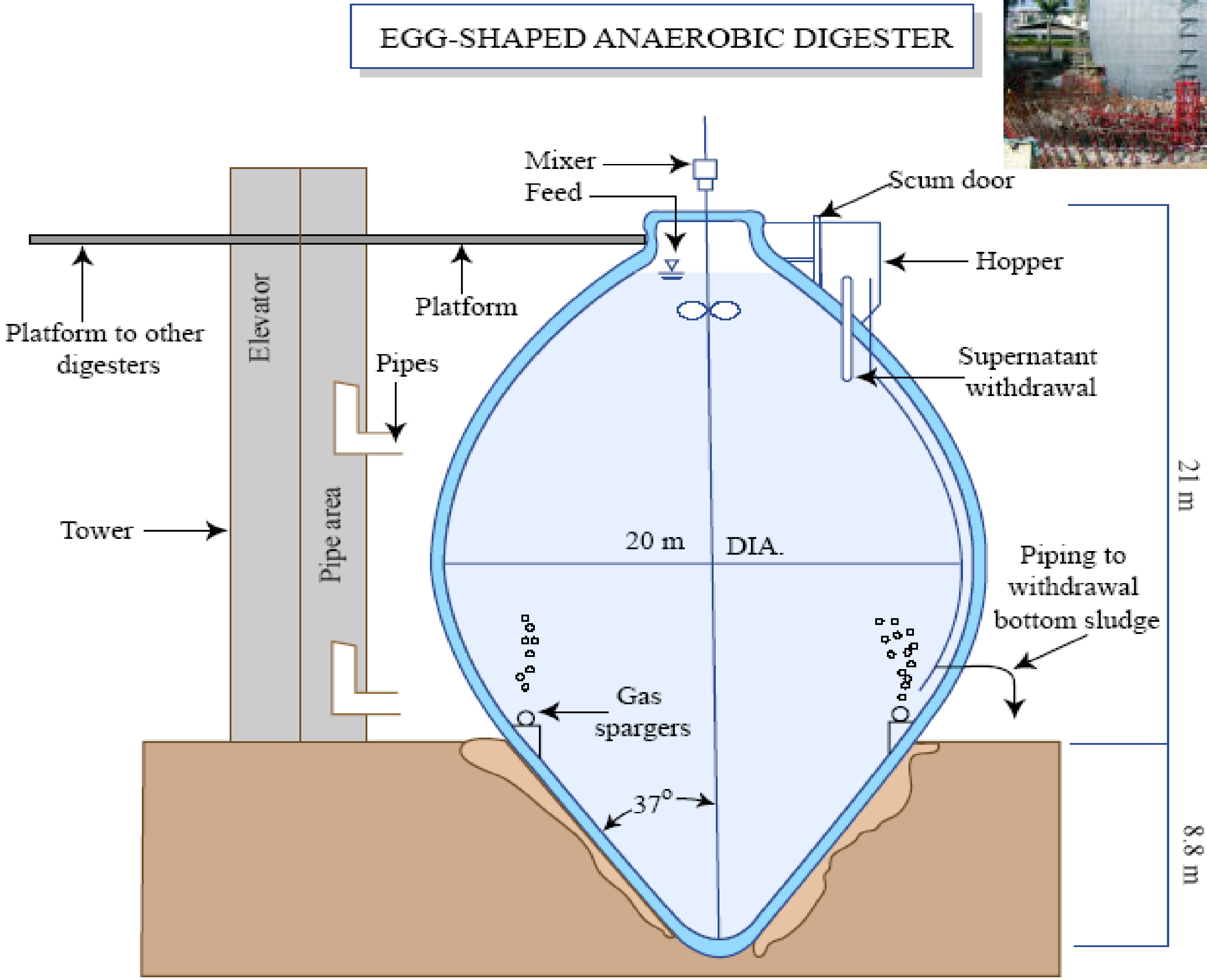
- In addition to landfill, anaerobic digesters have been used for decades to treat organic solid waste, including agriculture waste, sewage sludge, etc.

- Hong Kong DSD has operated the sludge anaerobic digesters for many years and generate biofuel (methane) to supply electricity to the sewage treatment works.

- Merits of anaerobic co-digestion of food waste with sewage sludge
  - ✓ Production of methane
  - ✓ Volume reduction (expressed as VSR (volatile solid reduction), reducing cost for further disposal)

- Use existing infrastructure and expertise to **divert food waste** from landfill **for biogas production**.

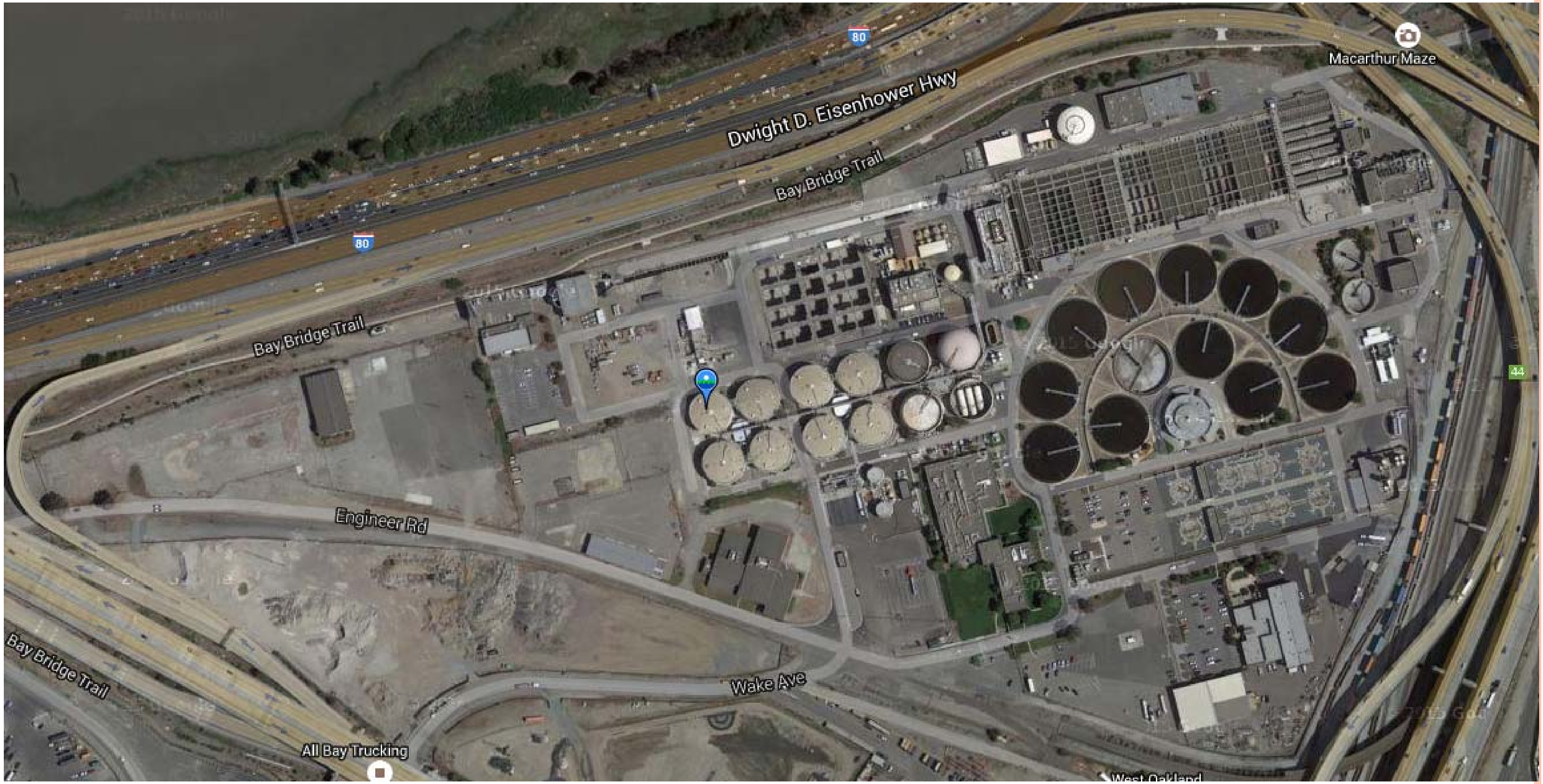
Anaerobic digester



Co-digestion at a US wastewater treatment plant

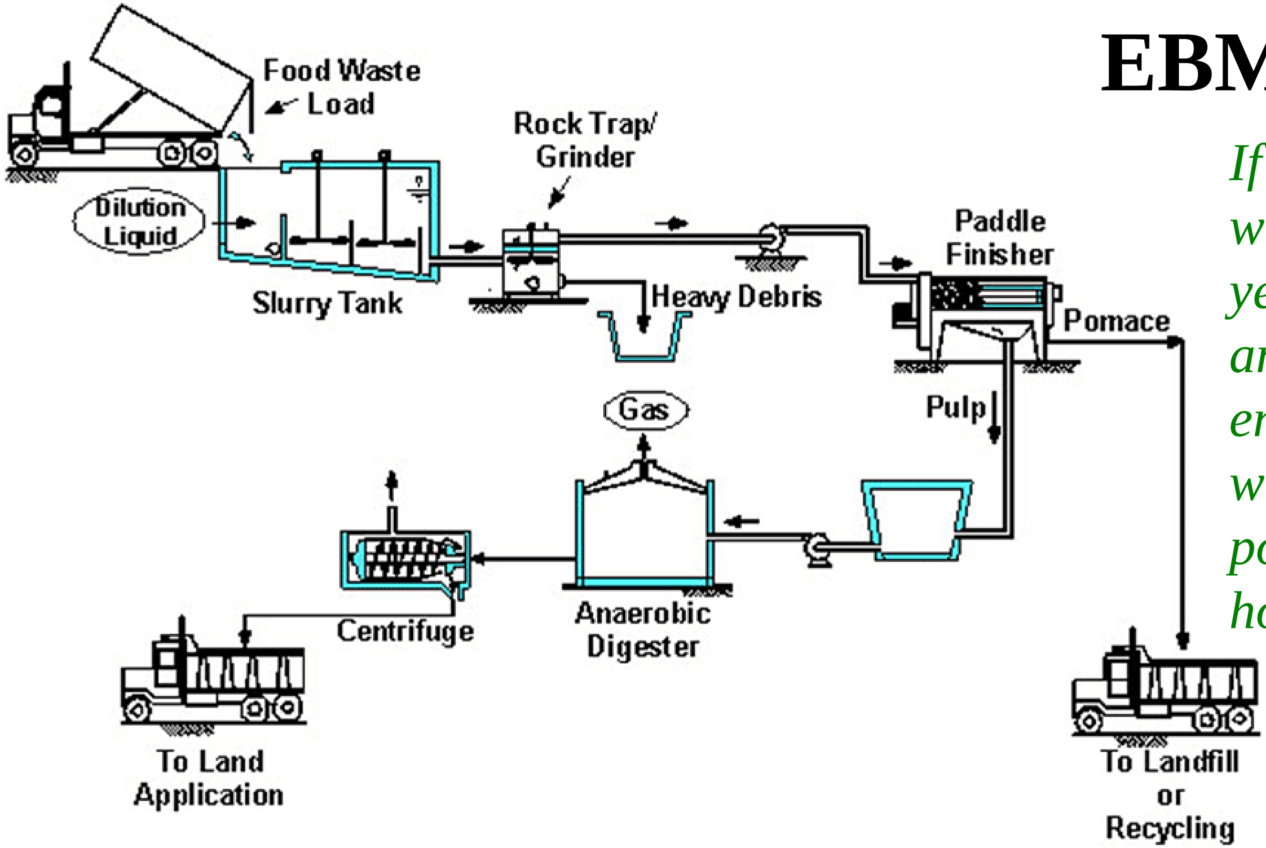
If there is excess capacity in the anaerobic digesters, food waste can be added to generate more energy. In California alone there are almost 140 wastewater treatment facilities that utilize anaerobic digesters, with an estimated excess capacity of **15-30%**.

Turning Food Waste into Energy at the **East Bay Municipal Utility District (EBMUD)**



http://www3.epa.gov/region9/waste/features/foodtoenergy/index.html

EBMUD Process



If 50% of the food waste generated each year in the U.S. was anaerobically digested, enough electricity would be generated to power over 2.5 million homes for a year.

To digest food waste in anaerobic digesters, food waste must be

1) pre-treated into a slurry in the slurry tank
2) grinded into small pieces of 2 inches
3) to remove heavy debris.
4) added to the anaerobic digester as pulp after going through the paddle finisher.

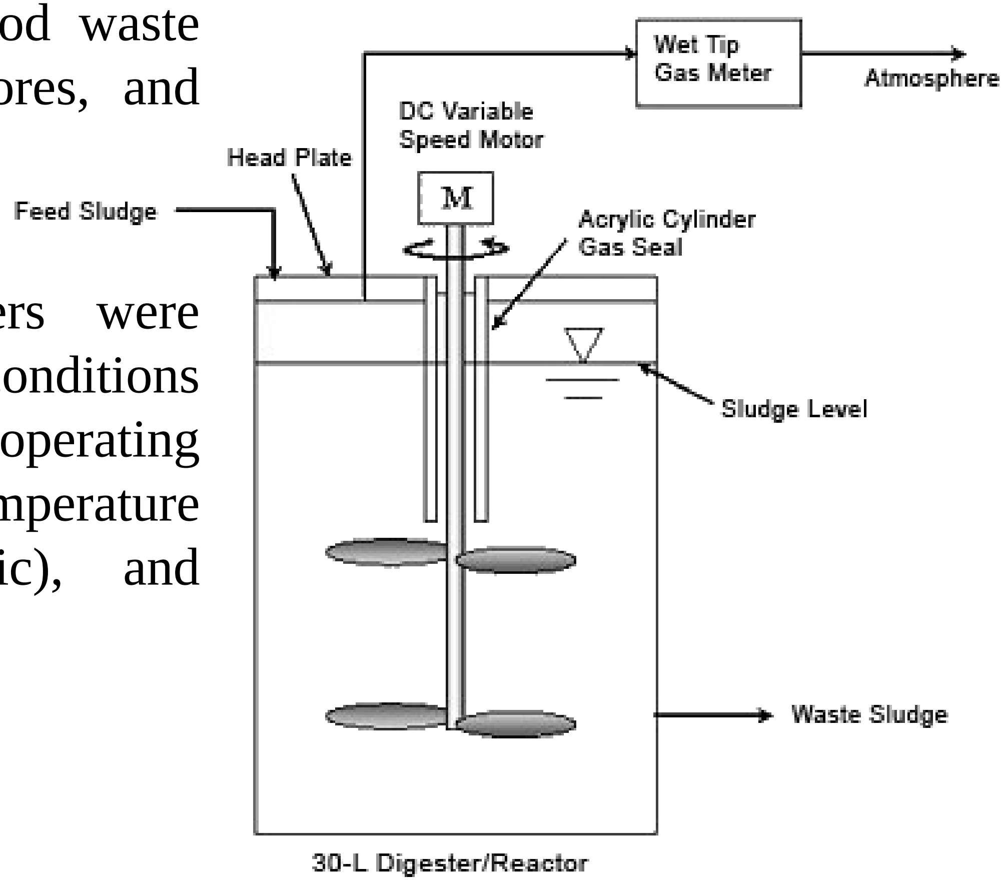
http://www3.epa.gov/region9/waste/features/foodtoenergy/index.html

Research on EBMUD Process

- To further study this technology, the EPA awarded EBMUD with a grant to investigate the benefits and limitations of anaerobically digesting food waste from restaurants, grocery stores, and other food handling facilities.

- EBMUD laboratory digesters were operated under a variety of conditions to determine the optimal operating conditions, like temperature (mesophilic vs thermophilic), and retention times.

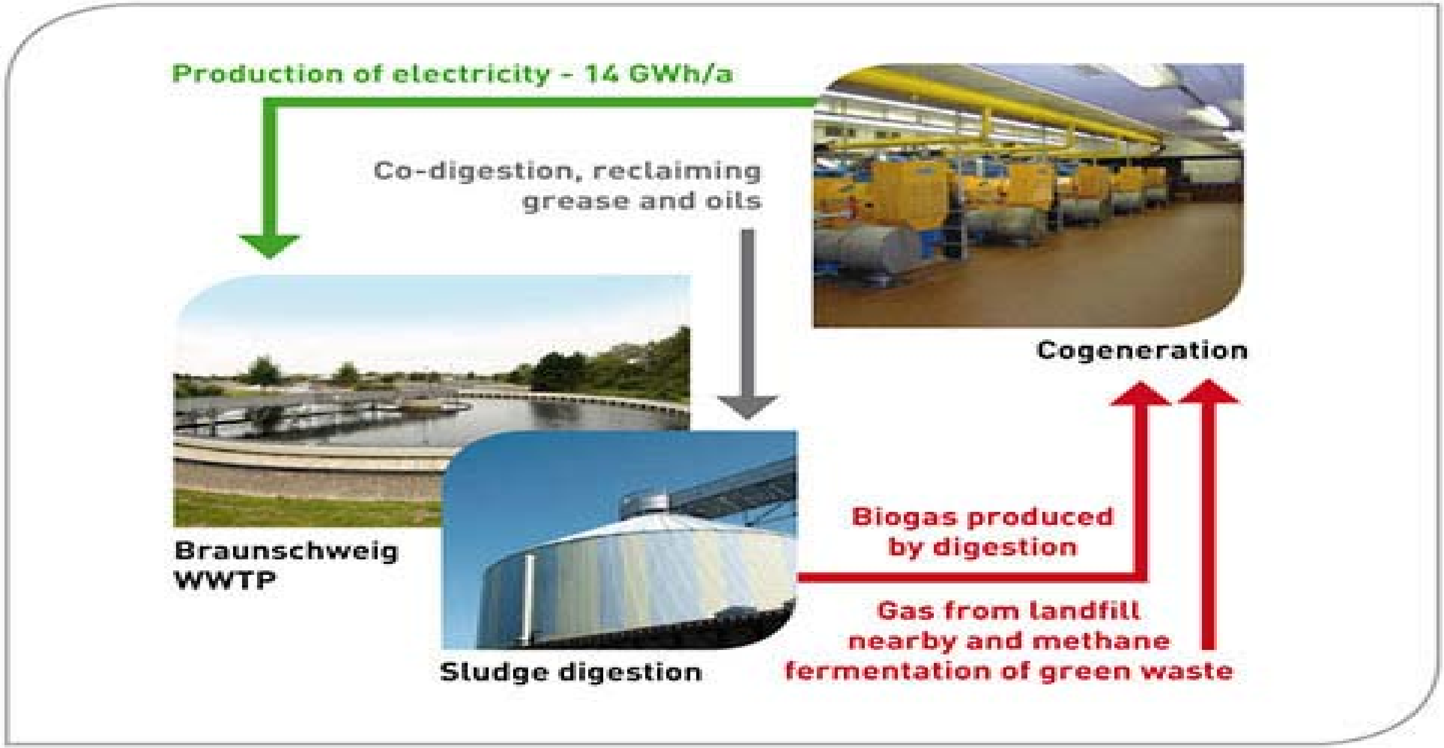
EBMUD laboratory digesters



http://www3.epa.gov/region9/waste/features/foodtoenergy/ebmud-study.html

Co-digestion at a Germany wastewater treatment plant

Braunschweig wastewater treatment plant



This plant currently achieves 100% electricity self-supply (energy neutral).

Plant with biological sewage treatment and thermophilic digestion of sludge.

- Capacity (Sewage flow): 52,000 m^3/day.
- Co-digestion of sludge with biowaste (grease and oil).
- Recycling of biogas from landfill.
- Recycling of methane from fermentation of green waste nearby.

Why we need to study co-digestion at Hong Kong?

Why cannot simply follow the experience of the oversea projects?

A general principle in co-digestion:

Characteristics of food waste and sludge decide the co-digestion feasibility and the operation parameters.

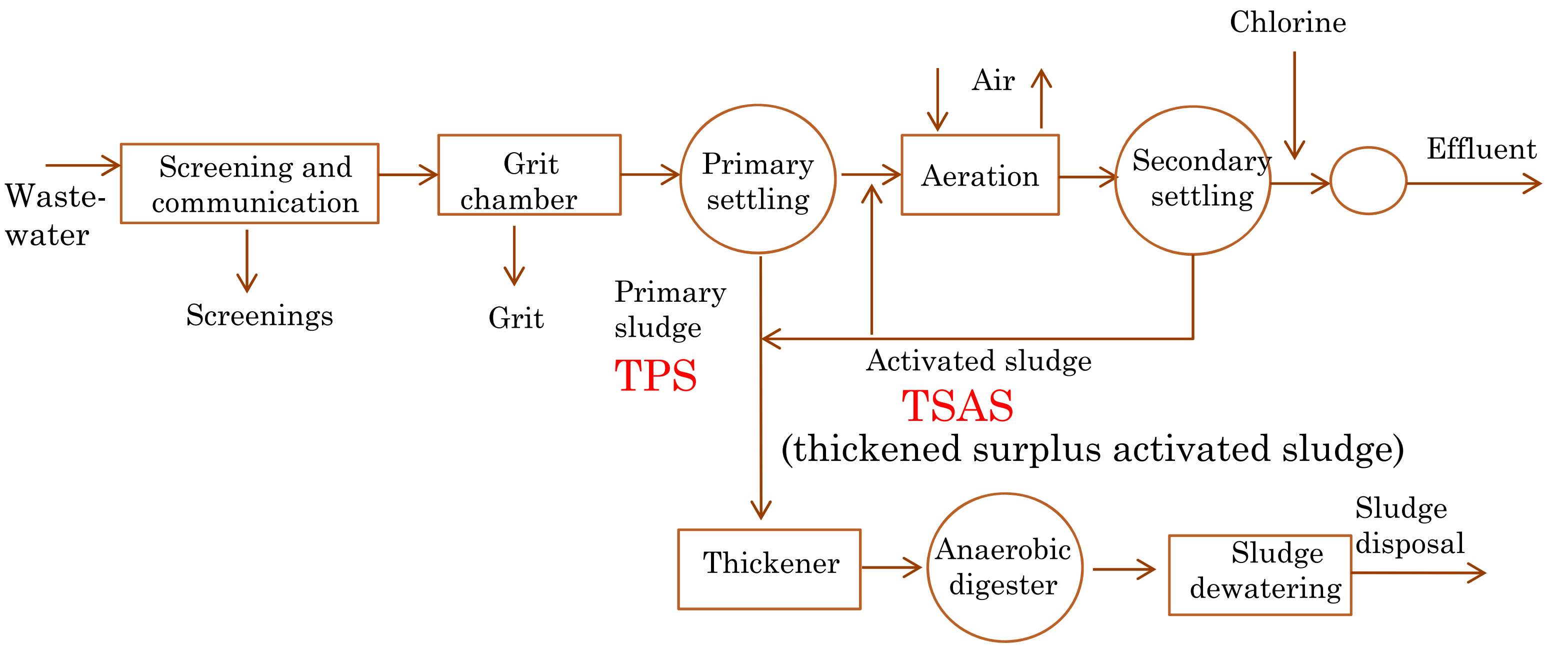
Research objectives of this study

The **feasibility** and **operational parameters** for food waste co-digestion with sewage sludge

- Effect of **salinity** on the co-digestion process
- Effect of **food waste/sewage sludge ratios**
- Effect of **HRT (hydraulic retention time)**

Combined feeding sewage sludge

Sources of sludge in a typical secondary municipal wastewater treatment plant



Feeding sewage sludge (FSS): **SWH**-STW: TPS /TSAS = 0.74/1(v/v)

TP-STW: TPS /TSAS = 4.5/1(v/v) (2014/08/14)

Note: TPS- thickened primary sludge;
TSAS-thickened secondary activated sludge

Composition of simulated food waste

Reported composition of food waste from different sources (% dry weight)

Food waste origin	Carbohydrates	Protein	Lipids	References
Household	55	17	13	(la Cour Jansen et al., 2004)
Household	61	14	14	(Hansen et al., 2007)
Urban (Households, markets, restaurants)	78	17	5	(Redonals et al., 2012)
University dining hall	64	15	17	(Ferris et al., 1995)
Military facilities	57	18	22	(Ferris et al., 1995)
Institution restaurant	64	21	12	(Yan et al., 2011)
This test	80	15	5	-

Spanish

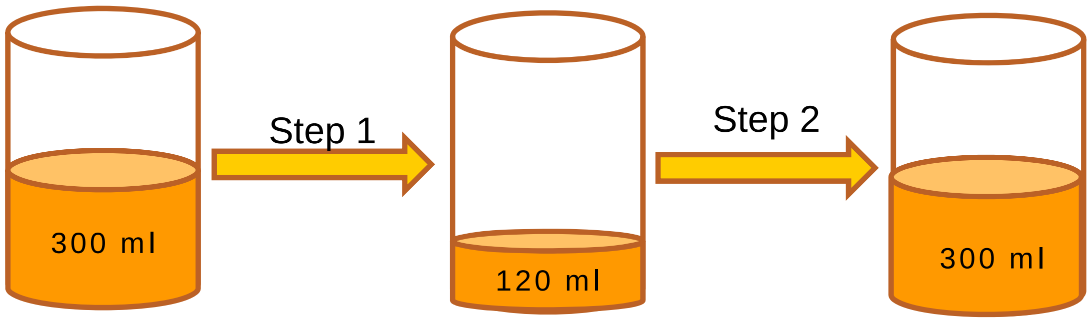
Based on food consumption pattern in HK

Preparation of simulated food waste

Category	Wet Weight (g)
Meat	103
Vegetable (lettuce)	162
Fruit (apple)	135
Steamed Rice	448
Bread	152

Reactor set-up (batch test)

- Batch test with pH manually controlled in the range of 6.8-7.5
  - ➢ Total working volume 300 ml
  - ➢ Two HRT tested: 10 days and 15 days, respectively
  - ➢ Two types of FSS sampled from SWH-STW (low-salinity) and TP-STW (high salinity), respectively



✓ Step 1: 60% of the **mixed slurry** was discharged from the bottle

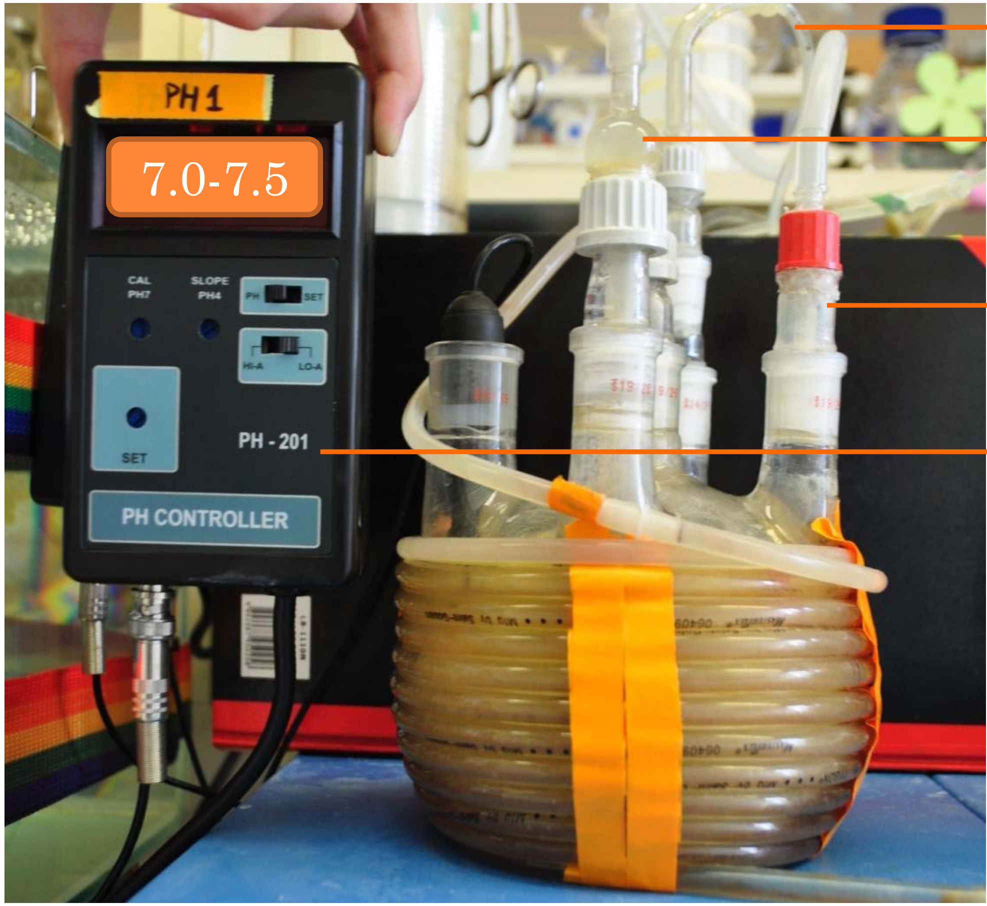
- HRT 10 days--- 60% of the sludge will be discharged every 6 days
- HRT 15 days--- 60% of the sludge will be discharged every 9 days

✓ Step 2: Add the **feed** (the mixture of FSS (feeding sewage sludge) and FW (food waste)) into the bottle

- Four different ratios of FW:FSS at 8:2 (aa), 5:5 (bb), 2:8 (cc) and 0:10 (00).

Reactor set-up (semi-continuous)

- Temperature: (35 ±1) ºC
- Working volume: 800 ml



Gas collection Tedlar® Gas Sampling Bag

Liquid sampling

pH controlling: 200 g/l Na_2CO_3

pH controller

R1: HRT 25 days, FW:FSS=5:5

R2: HRT 25 days, FW:FSS=2:8

R3: HRT 25 days, FW:FSS=0:10

R4: HRT 15 days, FW:FSS=2:8

Chemical analysis

- Gas Phase
  - Biogas component and concentration (*GC-TCD,HP*)
  - Biogas volume (*syringe*)
- Liquid Phase
  - Total organic carbon (*TOC-V CPH, SHIMADZU*）
  - NH_4^+-N (UV-160A, SHIMADZU)
  - VFAs & alcohols (*GC-FID, AGILENT*)
- TS (total solid) and VS (volatile solid)
  - Muffle Oven

Results of the batch tests - HRT 10 days

Methane yield and VS reduction (VSR)

Reactor No.	HRT (d)	FW: FSS	1st batch CH_4 (ml)	1st batch VSR	2nd batch CH_4 (ml)	2nd batch VSR	3rd batch CH_4 (ml)	3rd batch VSR	4th batch CH_4 (ml)	4th batch VSR	5th batch CH_4 (ml)	5th batch VSR
TP00-10	10	0:10	**531**	38%	**559**	38%	**538**	35%	**570**	35%	**512**	32%
TPaa-10	10	8:2	42	**65%**	171	**53%**	176	**55%**	174	**61%**	136	**62%**
SWH00-10	10	0:10	**503**	37%	**536**	36%	**596**	43%	**501**	31%	**579**	41%
SWHaa-10	10	8:2	52	**64%**	156	**51%**	296	**47%**	89	**54%**	72	**51%**
SWHbb-10	10	5:5	93	**42%**	170	**52%**	223	**57%**	156	**61%**	155	**55%**
SWHcc-10	10	2:8	273	**48%**	280	**49%**	263	**48%**	228	**43%**	215	**54%**

- Co-digestion had positive impact on VSR, but methane yield was lower in co-digestion reactors.
- No significant difference has been observed for the saline (TP) and the non-saline (SWH) sludge.

Note: ratios of FSS: FW at 10:0 (00), 8:2 (aa), 5:5 (bb) and 2:8 (cc)

Results of the batch tests - HRT 15 days

Methane yield and VS reduction (VSR)

Reactor No.	HRT (d)	FW:FSS	1st batch		2nd batch		3rd batch		4th batch		5th batch	
			CH_4 (ml)	VSR	CH_4 (ml)	VSR	CH_4 (ml)	VSR	CH_4 (ml)	VSR	CH_4 (ml)	VSR
TP00-15	15	0:10	**584**	35%	**515**	36%	**563**	32%	**537**	33%	**548**	34%
TPaa-15	15	8:2	91	**63%**	235	**51%**	105	**65%**	131	**61%**	131	**57%**
SWHaa-15	15	8:2	66	**63%**	107	**57%**	101	**60%**	176	**58%**	113	**57%**
SWHbb-15	15	5:5	91	**50%**	208	**56%**	123	**62%**	143	**55%**	111	**50%**
SWHcc-15	15	2:8	300	**53%**	226	**57%**	252	**66%**	271	**53%**	250	**52%**

- Co-digestion had positive impact on the VSR, yet lower methane yields was observed in those co-digestion reactors.
- No significant improvement VSR at HRT of 15 days compared with HRT of 10 days.

Note: ratios of FSS: FW at 10:0 (00), 8:2 (aa), 5:5 (bb) and 2:8 (cc)

Results of the batch tests - TOC

TOC concentrations in the batch reactors

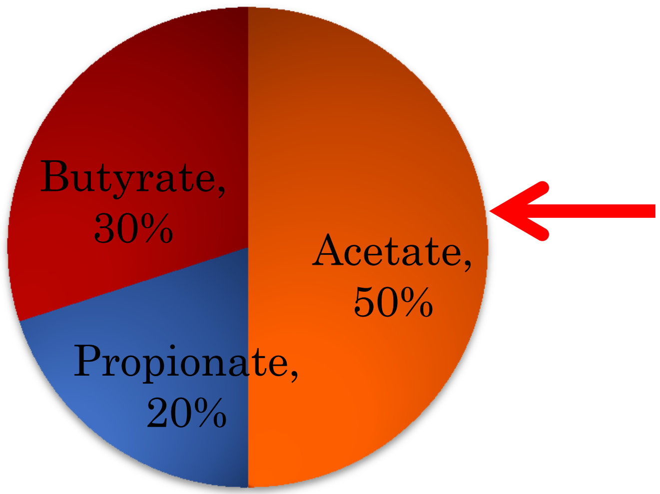
HRT 10 d	TOC (mg/l)				
	1st batch	2nd batch	3rd batch	4th batch	5th batch
TP00-10	300	180	210	165	330
TPaa-10	**3050**	**5010**	**7740**	**8850**	**8970**
TPbb-10	**2100**	**4980**	**6150**	**6720**	**6870**
TPcc-10	200	**2610**	**2700**	**1830**	**2310**
SWH00-10	200	480	780	1080	1230
SWHaa-10	**3100**	**7170**	**8610**	**9300**	**11730**
SWHbb-10	**2250**	**5190**	**6750**	**7050**	**6530**

- Co-digestion resulted in higher TOC in liquid.
- It was the same for both HRT of 15 days and HRT of 10 days.
- Food waste was digested but not converted into methane yet.

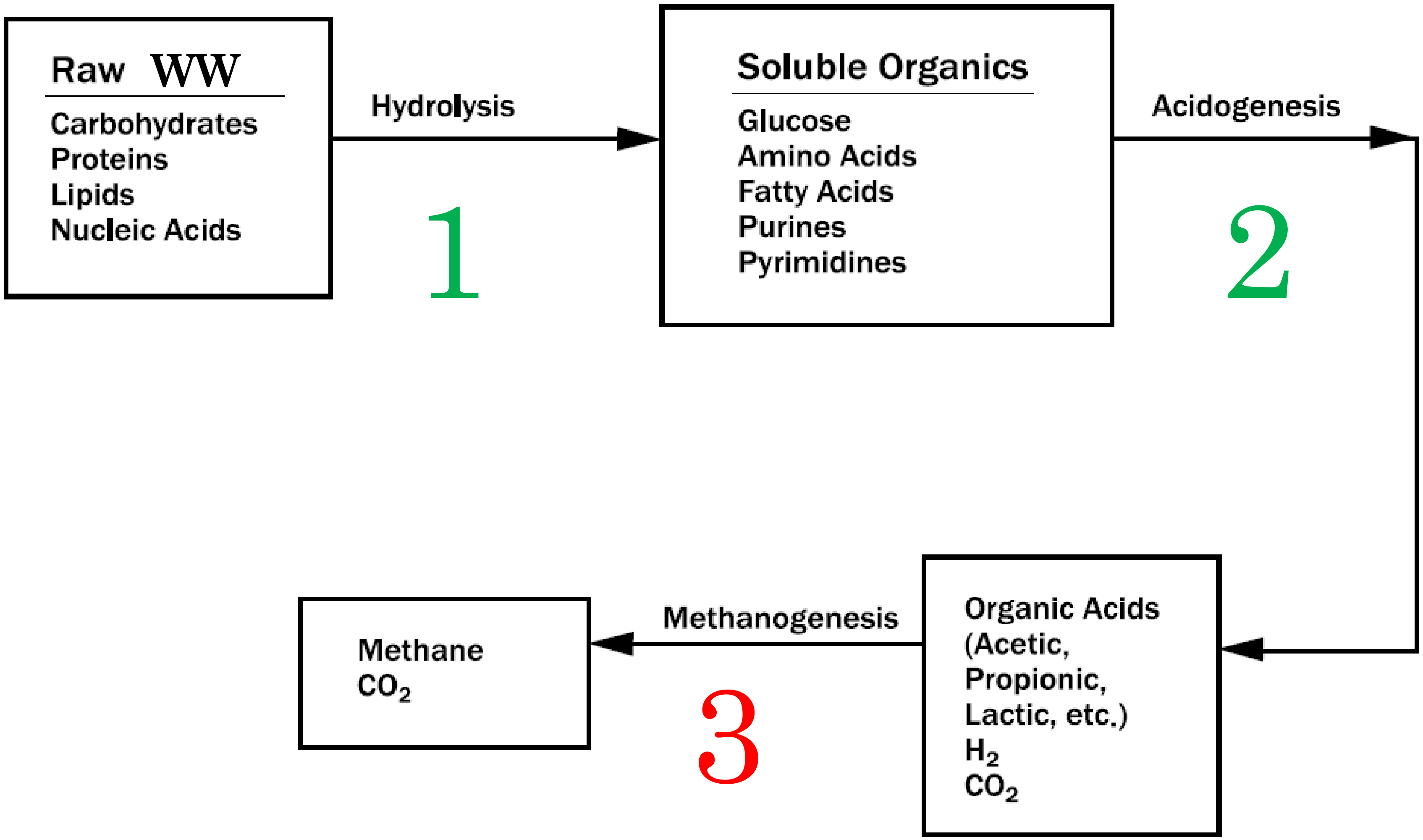
TPaa-15	**3420**	**6180**	**8070**	**8640**	**8850**
TPbb-15	**2850**	**3330**	**5460**	**6480**	**4530**
TPcc-15	140	**1200**	**1860**	**2280**	**2160**
SWH00-15	120	330	720	1830	600
SWHaa-15	**3150**	**6690**	**8730**	**9210**	**9690**
SWHbb-15	**5040**	**5520**	**7440**	**7410**	**7380**
SWHcc-15	180	**1200**	**2070**	**3090**	**3150**

Results of the batch tests – VFAs as TOC

- **VFAs (volatile fatty acids)** were the **major fermentation by-products** in the liquid phase, accounting **98%-99% of the total dissolved organics**.
- Significant Acetate accumulation in the co-digestion reactors, where **acetate** accounts for ~**50%** in the total, and the **butyrate** and **propionate** account around **30%** and **20%,** respectively.



Proportion of VFAs in the liquid phase of co-digestion reactors



Microbial reactions in anaerobic treatment

Analysis on the results of the batch test

Possible reasons for the insufficient methane production in co-digestion batch reactors

- **Sludge feeding amount and frequency:**

The **feeding frequency** is a little bit too **low** while the corresponding amount of refreshment **feed** (mixture of food waste and sewage sludge) is relatively **too high (60%)** for each batch, which may cause significant pH drop at each feeding. (*The reactor eats too much for each time.*)

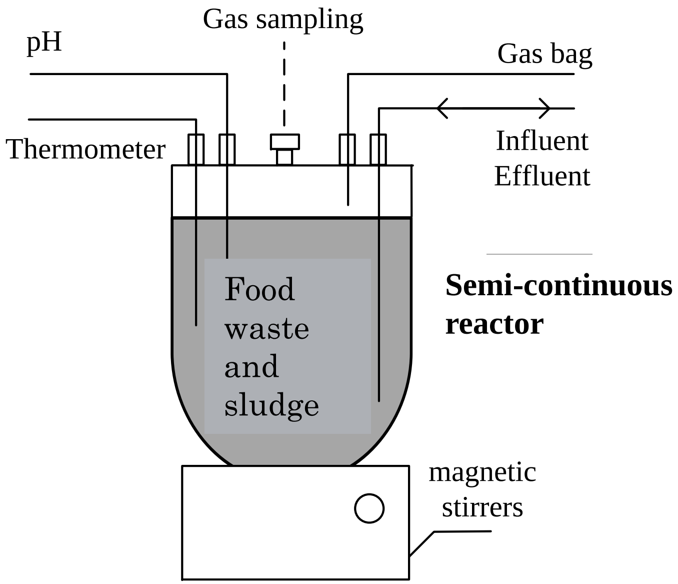
- **HRT:**

HRT of 10 days and 15 days might be **a little bit short** to build up methanogens populations. (*Not well digested.*)

- **pH control:**

No effective pH control (no pH automatic control device) in batch reactors. Especially in the first 12 hours of each batch, **pH dropped to as low as 4.5.** *(Too much sugar/carbohydrate.)*

Approaches in the semi-continuous reactor

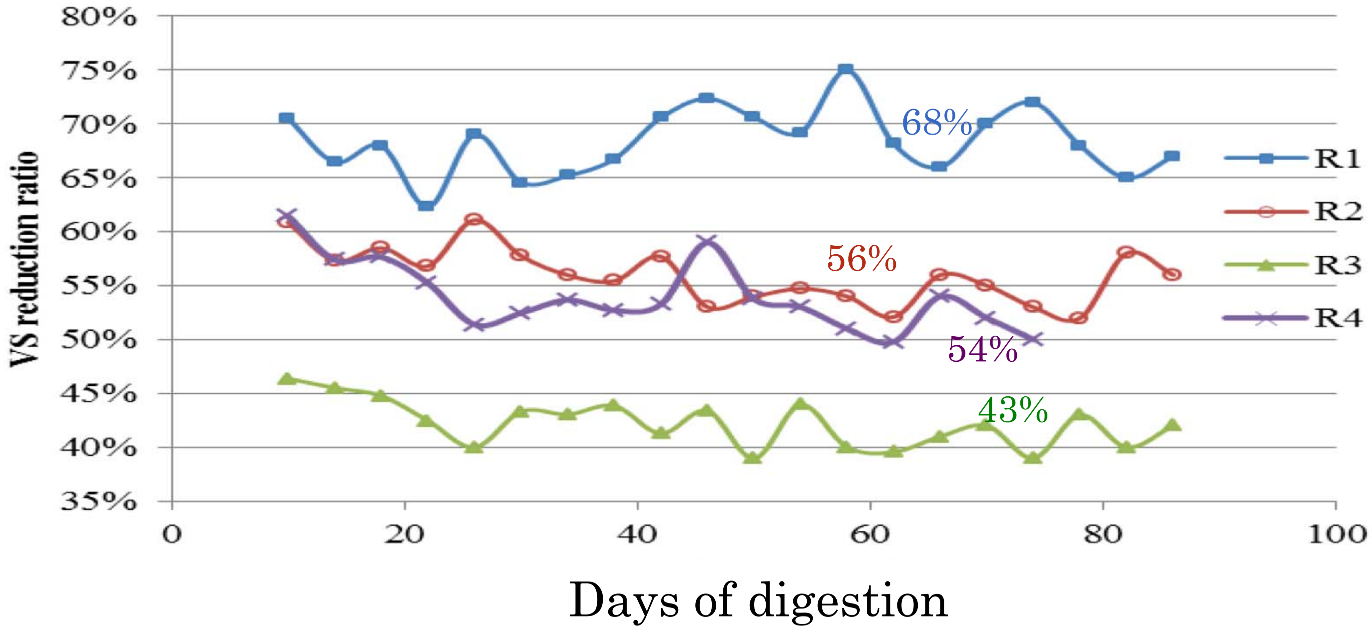


Only Tai Po FSS was tested in the semi-continuous reactor.

- **Longer HRT of 25 days** (*enough digestion time*) was investigated to compare with an HRT of 15 days.
- Three FW/FSS of **5:5, 2:8 and 0:10** were investigated, plus the reference control. (*delete the one of higher food waste to sludge ratio 8:2*)
- The reactor was **fed every other day** in a percent amount of 8% (HRT 25d) and 13% (HRT 15d), respectively, for reactors operated at HRT of 25 days and 15 days. (*eat more frequently, but less for each time, thus less shock of organic load*)
- **pH** was **controlled automatically** in the range of **6.8-7.5** (*good pH control for methanogenesis*)

Results of semi-continuous reactors (VSR)

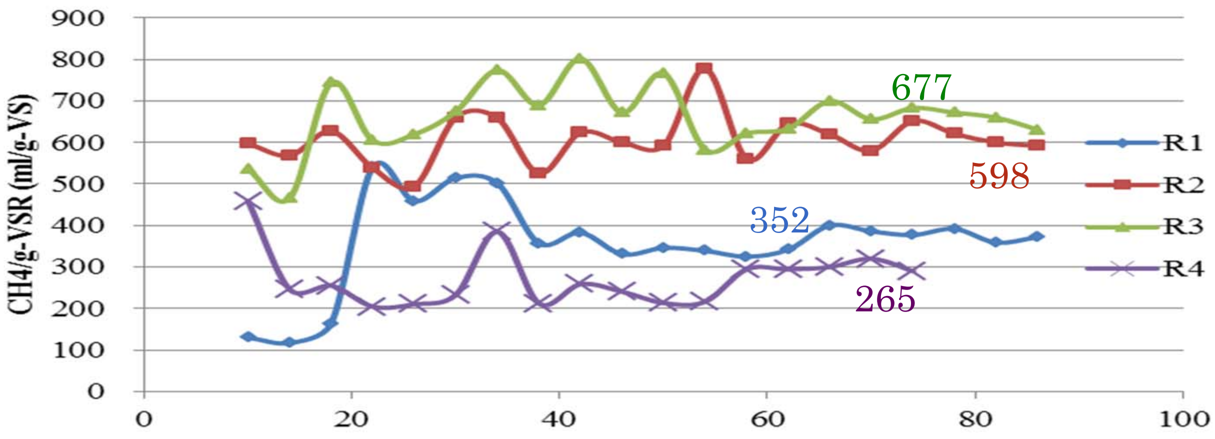
HRT 25d **R1: FW/FSS=5:5; R2: FW/FSS=2:8; R3: FW/FSS=0:10;**
HRT 15d **R4: FW/FSS=2:8**



- ✧ Consistent with the VSR results obtained in batch tests, a higher FW/FSS ratio corresponded with a higher VS reduction.
- ✧ HRTs (15d *vs* 25d) did not show significant impacts on VSR.

Results of semi-continuous reactors (methane production)

HRT 25d **R1: FW/FSS=5:5; R2: FW/FSS=2:8; R3: FW/FSS=0:10;**
HRT 15d **R4: FW/FSS=2:8**



- Methane yield (ml CH_4 per g $VS_{destroyed}$) of co-digestion at FW/FSS=2:8 was comparable to that in the sludge digester.
- The highest methane production was obtained at FW/FSS=2:8, considering both methane yield and VS reduction amount.

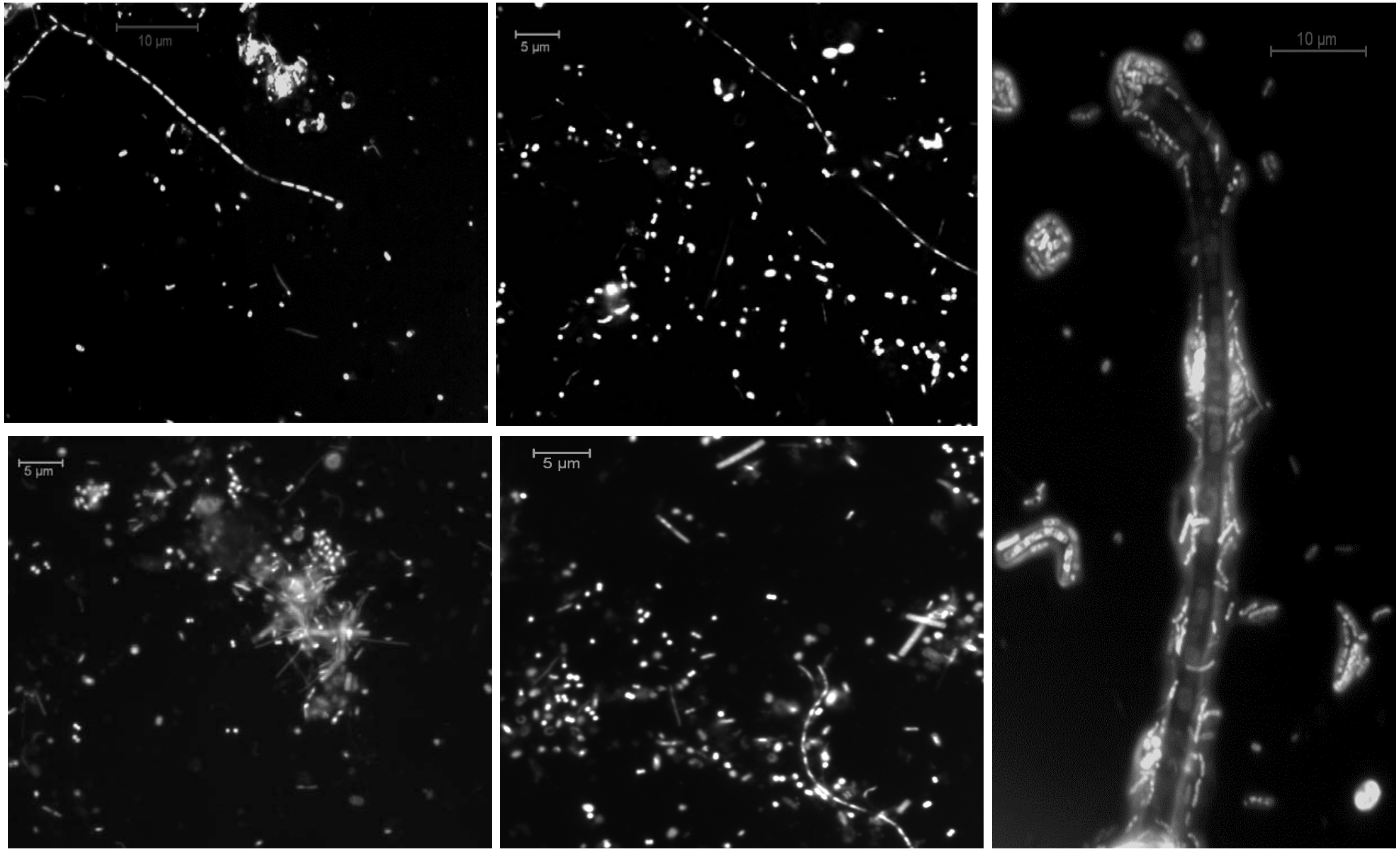
Table 4
Comparison of CH_4 yields during the mesophilic (~35 °C) digestion of sewage sludge, food waste and their mixture.

Substrate	CH_4 yield (lCH_4/gVS_{deg})	References
Sewage sludge	0.116	(Kim et al., 2003)
Sewage sludge (50%VS) + Food waste (50%VS)	0.215	(Kim et al., 2003)
Sewage sludge	0.318	(Sosnowski et al., 2008)
Food waste	0.234	(Sosnowski et al., 2008)
Sewage sludge (75%DS) + Food waste (25%DS)	0.439	(Sosnowski et al., 2008) Ratio (FW/FSS) = 1:3
Sewage sludge	0.269	(la Cour Jansen et al., 2004)
Food waste	0.395	(la Cour Jansen et al., 2004)
Sewage sludge (80%VS) + Food waste (20%VS)	0.326	(la Cour Jansen et al., 2004)
WAS (90%VS) + Food waste (10%VS)	0.186	(Heo et al., 2004)
WAS (50%VS) + Food waste (50%VS)	0.321	(Heo et al., 2004)
WAS (10%VS) + Food waste (90%VS)	0.346	(Heo et al., 2004)

WAS: waste activated sludge.

Iacovidou E et al.. 2012. Food waste co-digestion with sewage sludge - Realizing its potential in the UK. *Journal of Environmental Management*. 112, 267-274

Morphology of microorganisms in reactors under microscope



We may observe the shapes and count numbers of microorganisms under microscope. **But** it is difficult to know their names and functions.

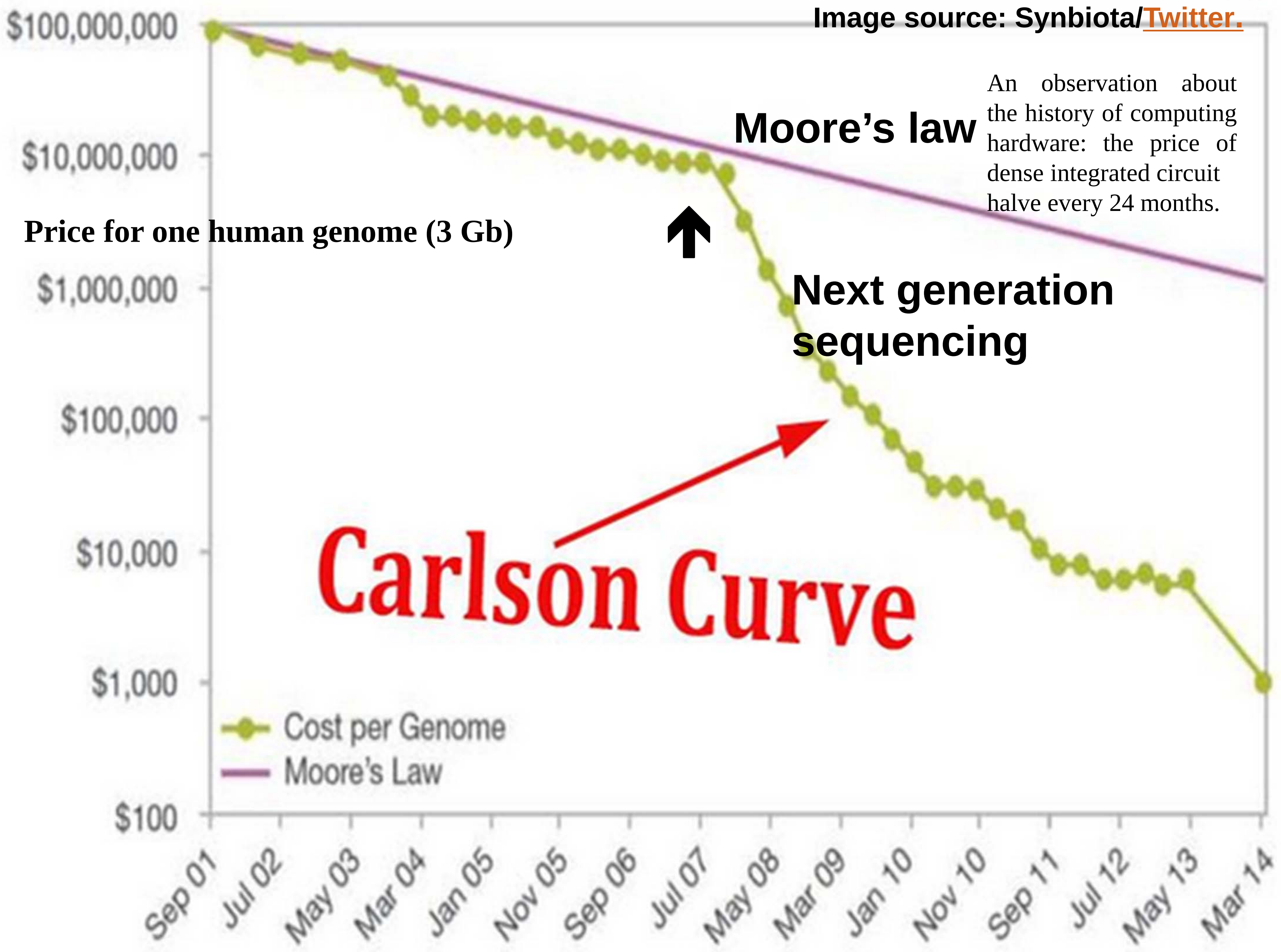


Image source: Synbiota/Twitter.
Moore’s law
An observation about the history of computing hardware: the price of dense integrated circuit halve every 24 months.
Price for one human genome (3 Gb)
Next generation sequencing
Carlson Curve
$100,000,000
$10,000,000
$1,000,000
$100,000
$10,000
$1,000
$100
Cost per Genome
Moore’s Law
Sep 01
Jul 02
May 03
Mar 04
Jan 05
Nov 05
Sep 06
Jul 07
May 08
Mar 09
Jan 10
Nov 10
Sep 11
Jul 12
May 13
Mar 14

Environmental Bioinformatics

A "new frontier" in Environmental Engineering

Bioinformatics : ***translation*** (from the different combinations of A, T, G and C to some biological terms, such as names of bacteria species and names of genes/enzymes) of **big data**, based on *databases (*like *"dictionaries").*

Bioinformatics : another kind of the "*microscope*" to study microorganisms in wastewater reactors. It tells us the names and functions of different microbial populations.

Next generation sequencing for microbial analysis

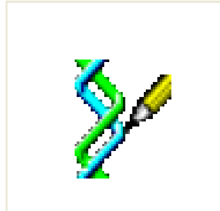
Slurry Samples

DNA extraction

Genomic DNA

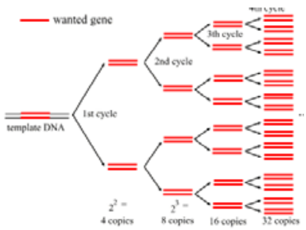
Illumina Hiseq

Illumina



Metagenomes

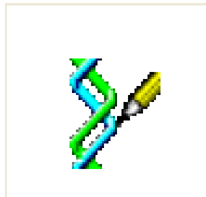
PCR amplification



Amplicons

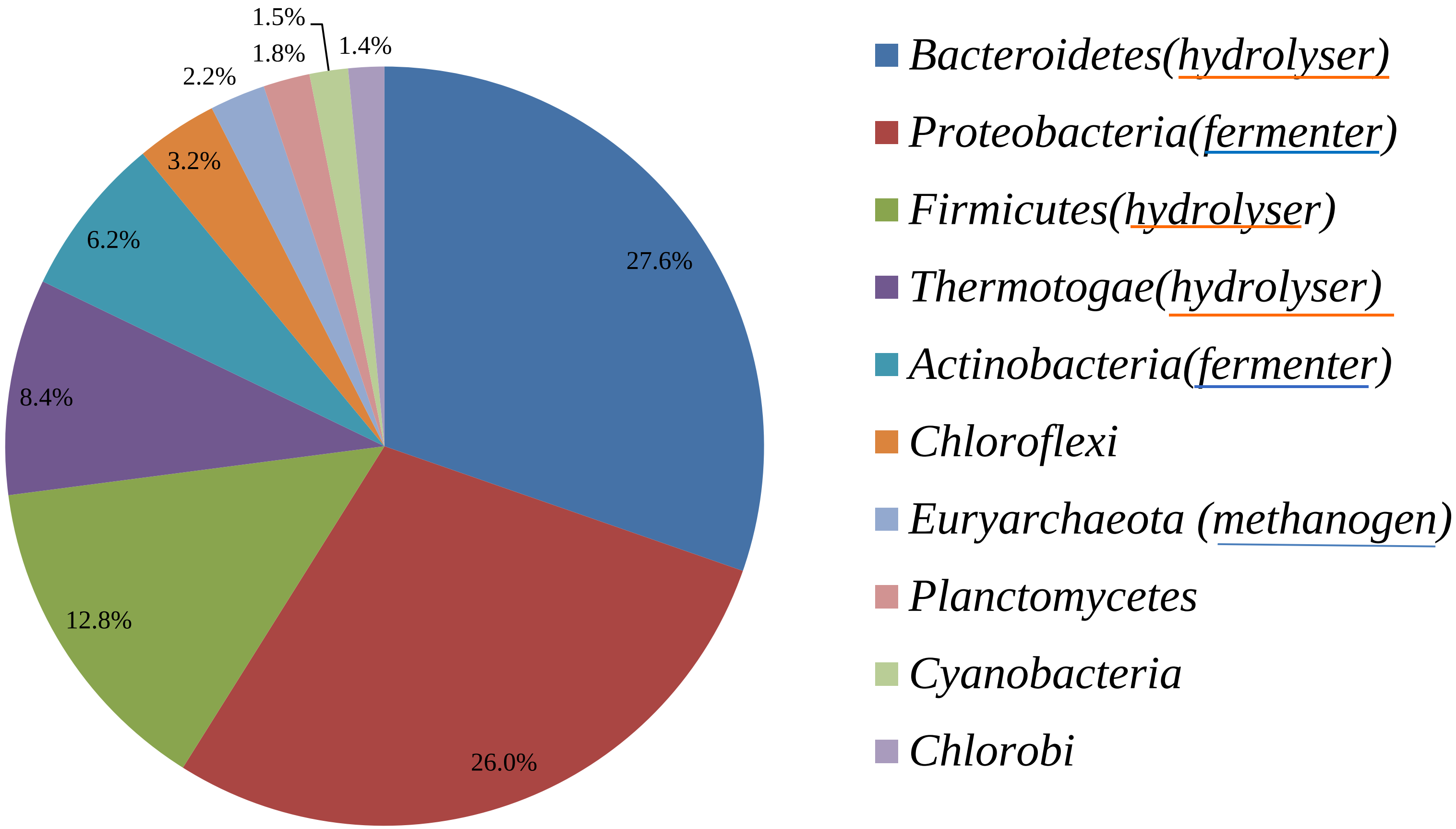
Roche GS FLX sequencer

454 pyro-sequencing



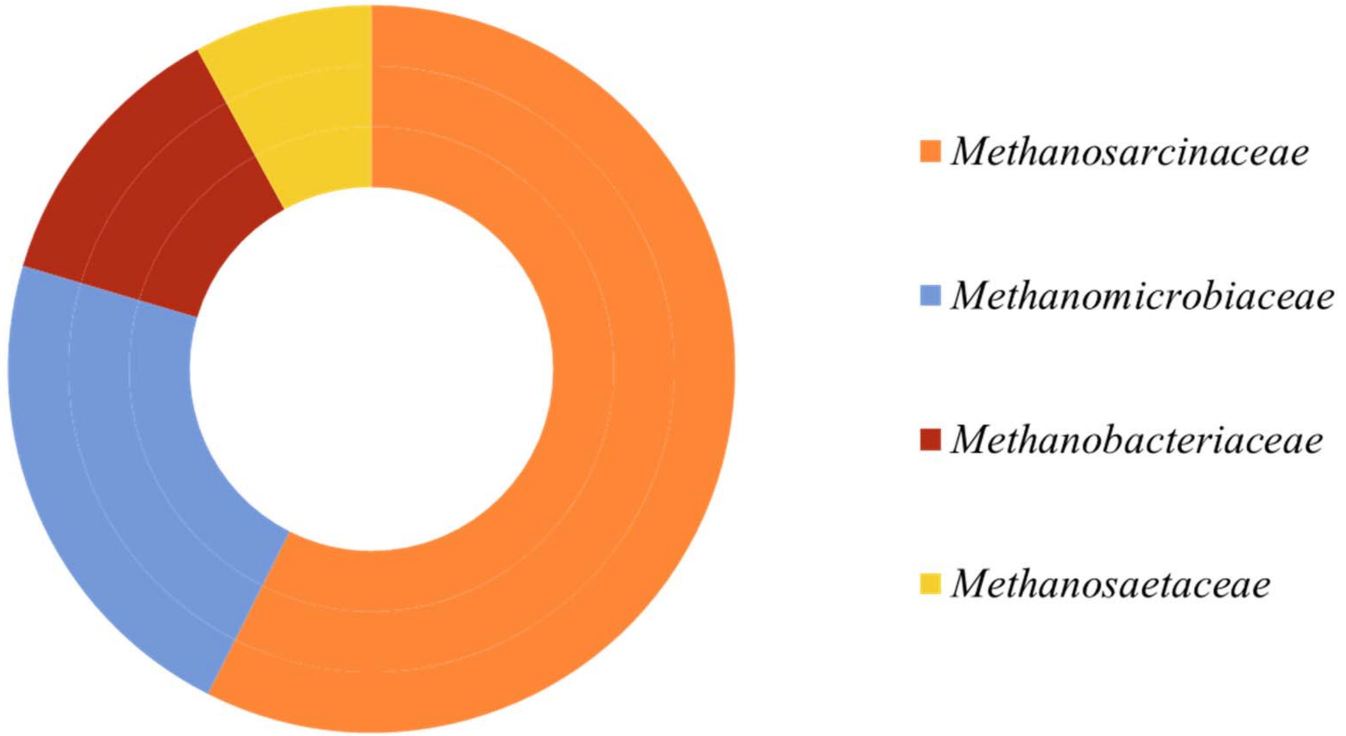
16S rRNA gene amplicon data

Classification of microorganisms at phylum level



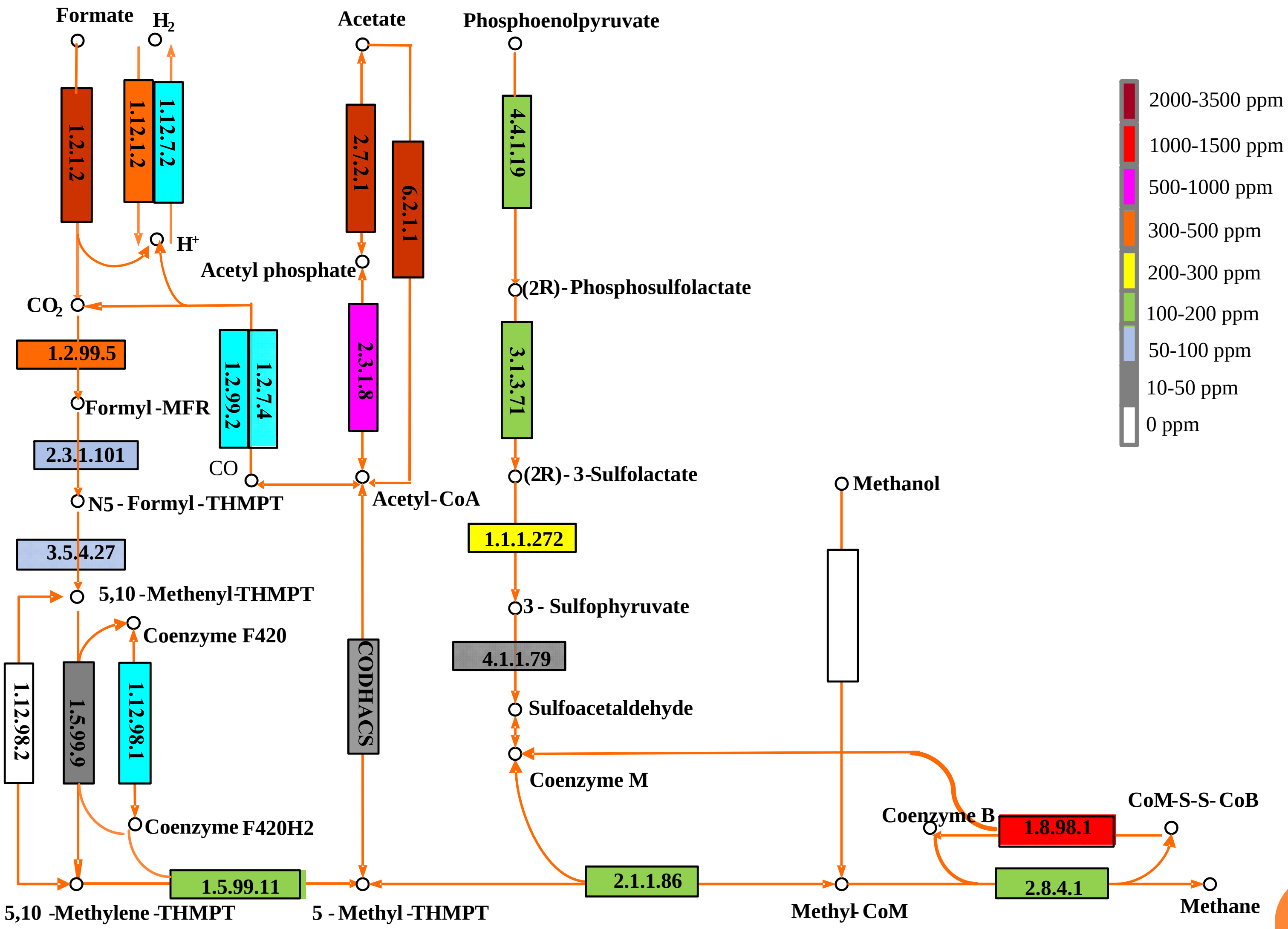
- *Bacteria* accounts for 96.1%, *Archaea 2.6%,* plus a minor part of unknown sequences.
- The top six phyla: *Bacteroidetes*, *Proteobacteria*, *Firmicutes*, *Thermotogae*, *Actinobacteria*, and *Chloroflexi*, are general hydrolysers and/or fermenters (acidogens).

Diversity of methanogens in the co-digestion reactor



- Both the hydrogenotrophic methanogens and acetoclastic methanogens were found in the reactors.
- *Methanosarcinaceae*, the methanogen growing well under higher acetate concentrations, was the most abundant methanogens identified, different from methanogens in digesters of sewage sludge.

Pathways of the methane production



Take-home messages

Co-digestion is one of the solutions to treat food waste.

Reactor operation and performance :

- ✓ Positive impact of co-digestion on VSR : the highest VSR of 68% was observed in the semi-continuous reactor at FW/FSS = 5:5.
- ✓ FW/FSS = 2:8 was the most appropriate ratio for co-digestion, considering both VSR (56%) and methanogen yield (0.6 m^3 CH_4/kg-$VS_{destroyed}$).
- ✓ A longer HRT of 25 days improved methane yield by >2 times than that at HRT of 15 days.

Microbial analysis :

- ✓ Major hydrolysers : *Bacteroidetes*, *Firmicutes*, and *Thermotogae*
- ✓ Major fermenters: *Proteobacteria* and *Actinobacteria*
- ✓ Major methanogens: *Methanosarcinaceae*

Future studies

- Scale up in larger reactor

- Effect of the mixing methods
- Longer HRT
- Higher food waste to sludge ratio
- The compositions of the food waste
- ……
- ……

Thank you

Your comments are welcome !