Effective Sewage Sanitation with Low CO_2 Footprint

Joan Colón, Aaron A. Forbis-Stokes, Lilya S. Ouksel, Marc A. Deshusses

Department of Civil and Environmental Engineering

Duke University, Durham, North Carolina, USA

Duke UNIVERSITY

Energy in Faecal Sludge … a Few Relevant Numbers

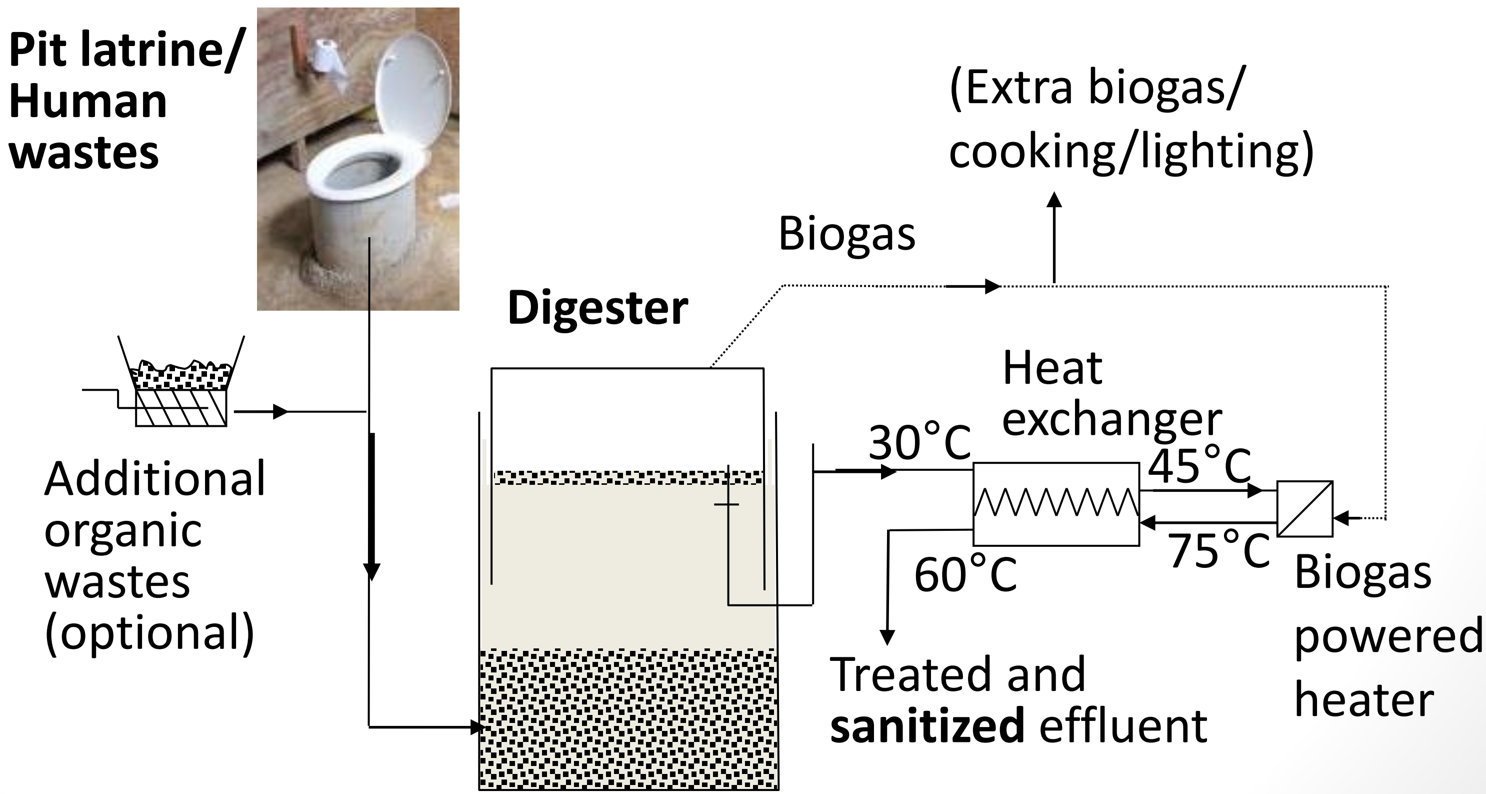
1 person: 400 g_{wet} feces and 1 L urine per day

- Heat 1 kg = 1 L water by 1 °C — 4180 J
- Vaporize 1 kg water — 2,260,000 J
- Burn 10 L = 6.4 g methane — 358,000 J
- Burn 10 g wood — ~200,000 J
- Burn 80 g dry feces (~400 g wet) — ~1,600,00 J
- Dry 400 g wet feces, burn solid — ~880,000 J
- Dry 400 g wet feces + 1 L urine, burn solid — requires 1,400,000 J

- Waste of 1 person digested anaerobically 860,000 J
  or about 10-15 Watts continuous (or 240-360 Wh per day)

A Self-Sanitizing Toilet

Our objective is to develop a **self-contained** and **energy neutral** sanitation technology that relies on anaerobic digestion to generate biogas then used to **heat-sterilize** the treated effluent.

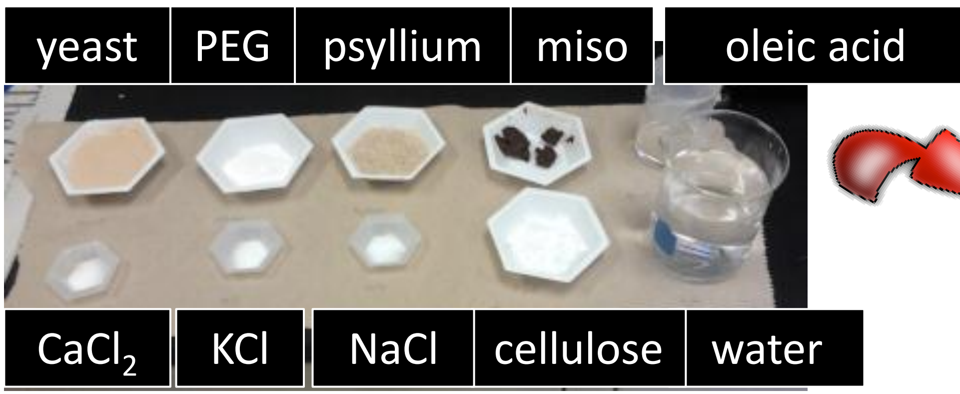


(diagram not to scale)

Feedstock for Anaerobic Digestion

SIMULANT HUMAN EXCRETA

Feces recipe: Adaptation of Wignarajah et al. (2006)
Urine recipe: Adaptation of Putnam (1974)



Most relevant properties

- COD, BOD
- Nitrogen content
- Salts content

Human excreta
Feces: Average of **350-400 g_{wet} p^{-1} d^{-1}** (WHO, 1992)
Urine: Average of **1 L p^{-1} d^{-1}** (WHO, 1992)

Faecal Sludge Simulant Properties

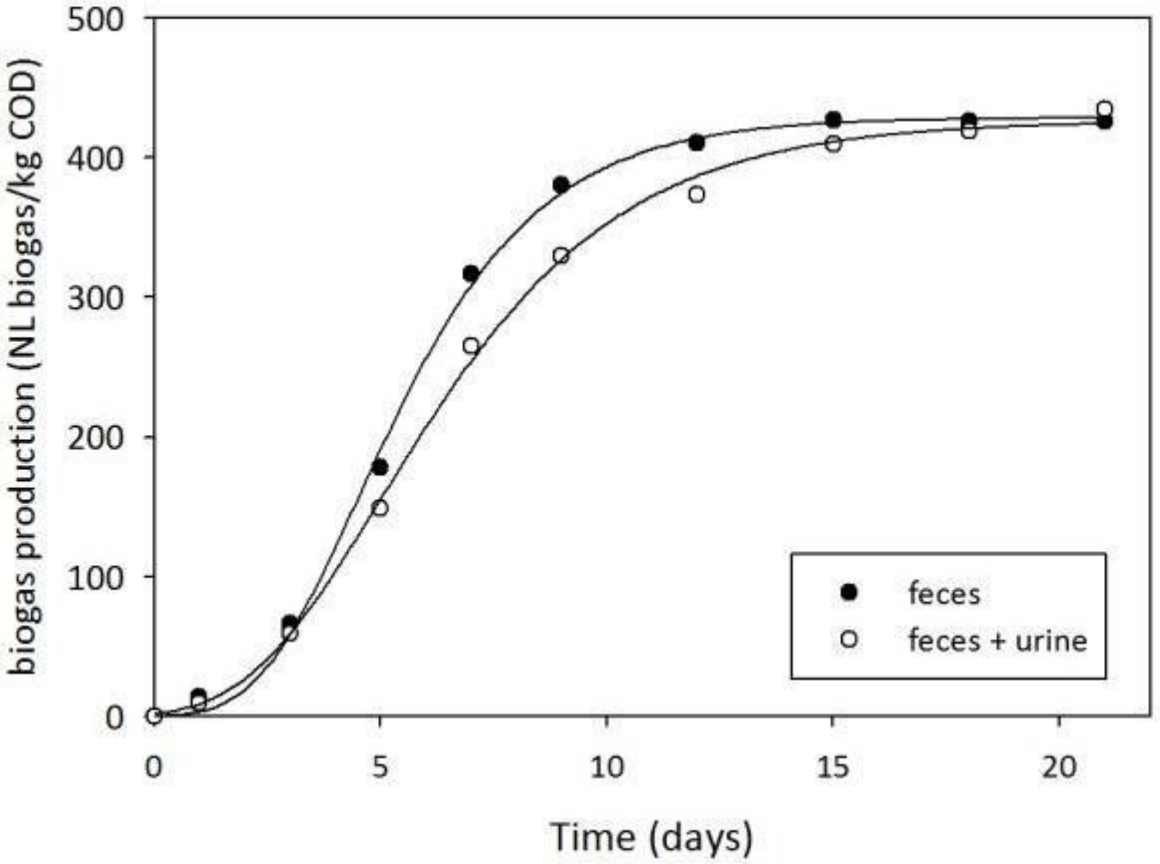
Properties	Simulant feces	Real feces	Properties	Simulant urine	Real urine
Moisture (%)	80	65-85[1]	Moisture (%)	97.6	95-98[4]
TS (%)	20	15-35[1]	TS (%)	2.4	2.5-3.7[4]
VS (%)	80	-	VS (%)	60	-
COD (g COD/g TS)	1.23	1.24 [2]	COD (g COD/l)	4.8	3.8-8.2[2]
CODs (g COD/g TS)	0.85	-	CODs (g COD/l)	0	-
CODdis (g COD/g TS)	0.38	-	CODdis (g COD/l)	4.8	-
N_{tot} (% dry matter)	2.55	2-3[3]	N-tot (mg/l)	5200	5000-8000[4]
N-NH_3 (% N_{tot})	3.02	<7[2]	N-NH_3 (mg/l)	197	<100[2]
			P-total (mg/l)	400	400-1000[4]
pH (1:5 w:v)	5.3	4.6-8.4	pH	6.05	6-8.2[4]
Conduct. (1:5 w:v, mS/cm)	5.7	-	Conduct. (mS/cm)	23	16-22[4]

(1) Wignarajah et al. (2006)
(2) Jönsson et al. (2005)
(3) Ganong (1983)
(4) Putnam (1974)

Example:
Simulant excreta: **7.2 g N p^{-1} d^{-1}**
Real excreta: **5.2 -8.2 g N p^{-1} d^{-1}**
(Uganda, Haiti, India, South Africa)

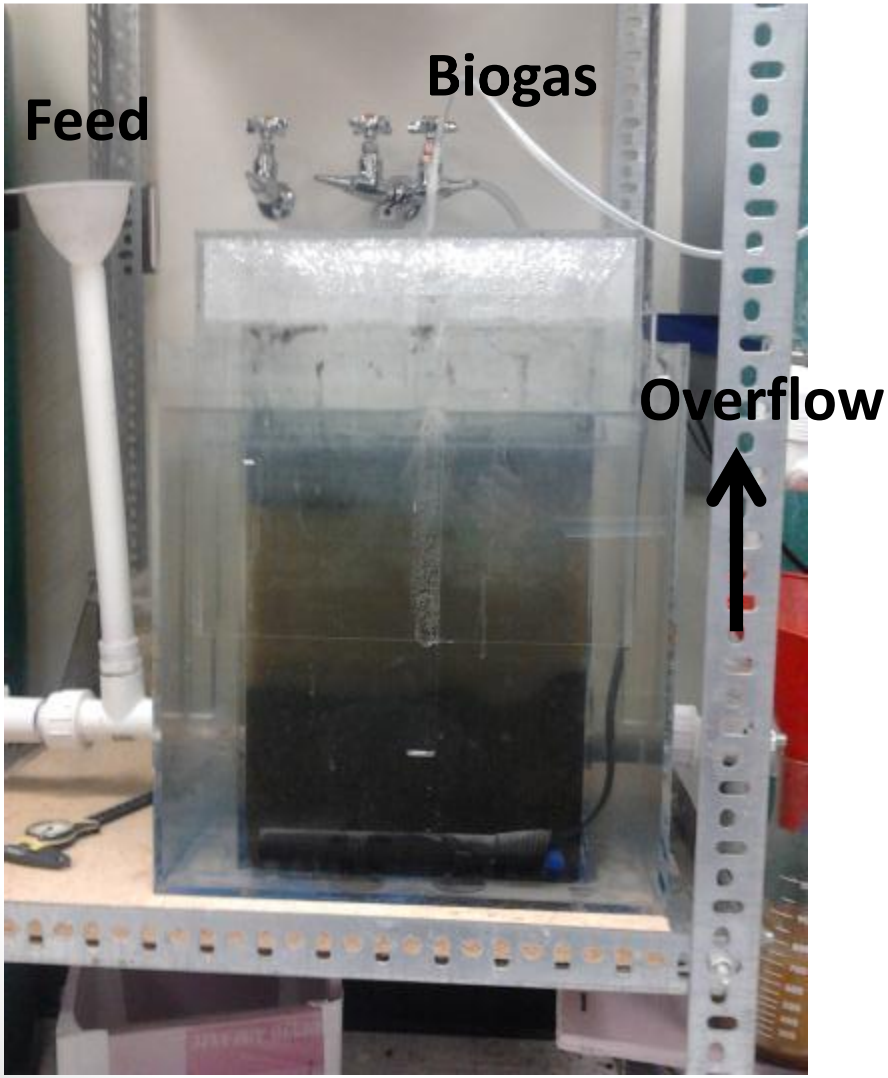
Anaerobic Digestion of Simulant Excreta

Biogas Potential Test
-feedstock
-inoculum
-monitor pressure
& gas composition



	Biogas yield (NL biogas/kg COD)	R_{max} (NL biogas kg^{-1} COD d^{-1})
Feces	428	71
Feces + urine	426	52

Anaerobic Digester



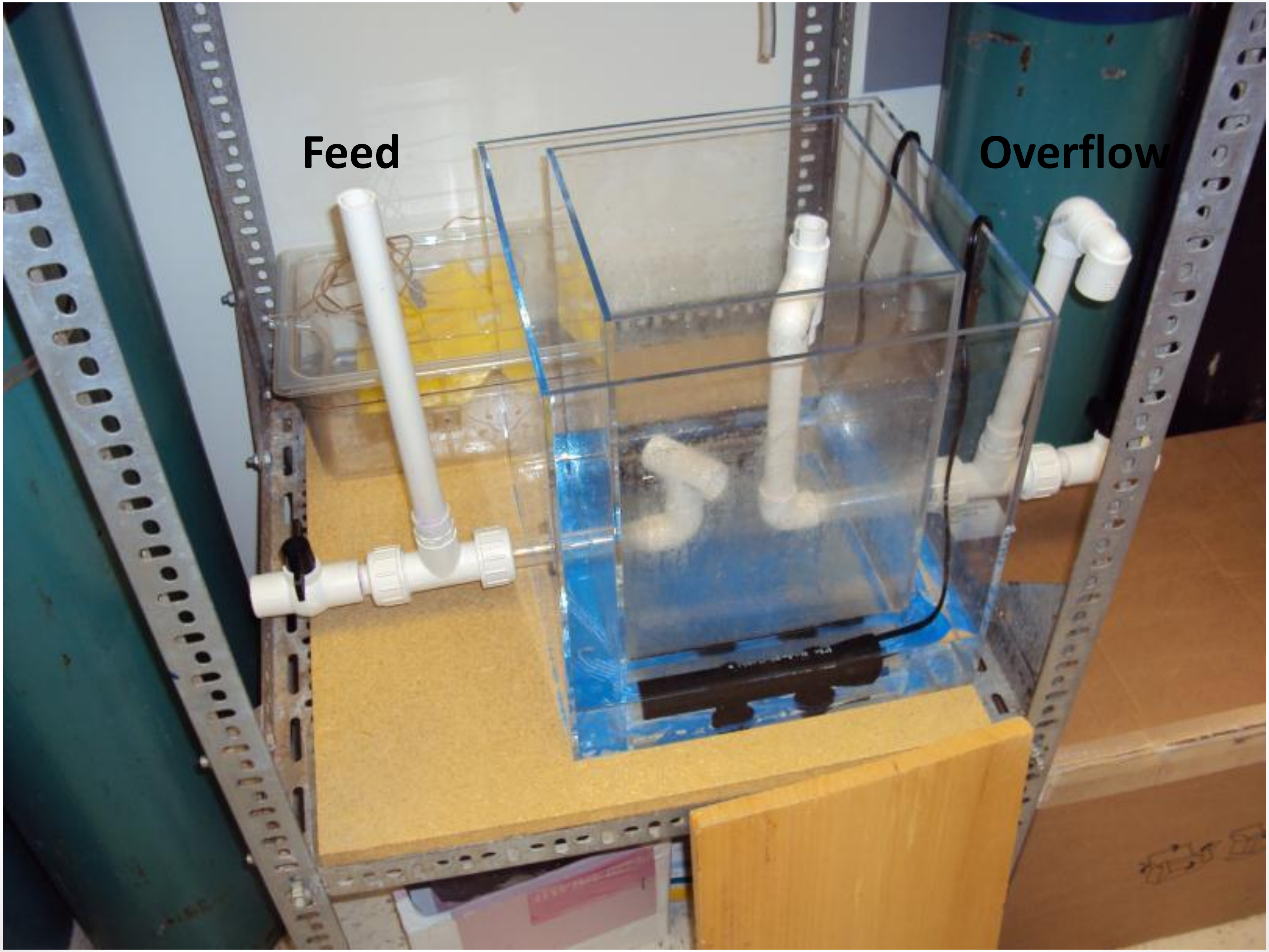
400 g_{wet} feces and 1 L urine per person per day is a reasonable assumption

10 person system – scaled down 1:33

17 L vol. HRT 40 days
OLR = 1.8 g COD/(L_{react} d)
0.13 g N/(L_{react} d)
T= 30 °C

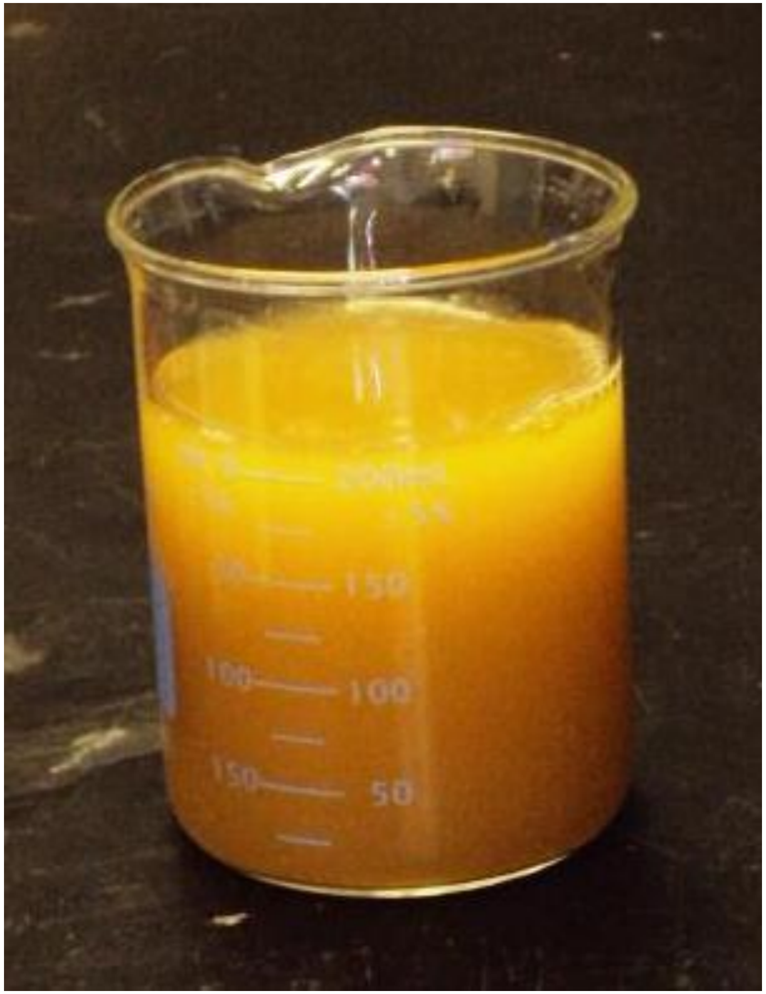
Daily feed
300 mL urine/d
120 g feces/d
Intermittent feed
No mixing

Anaerobic Digester

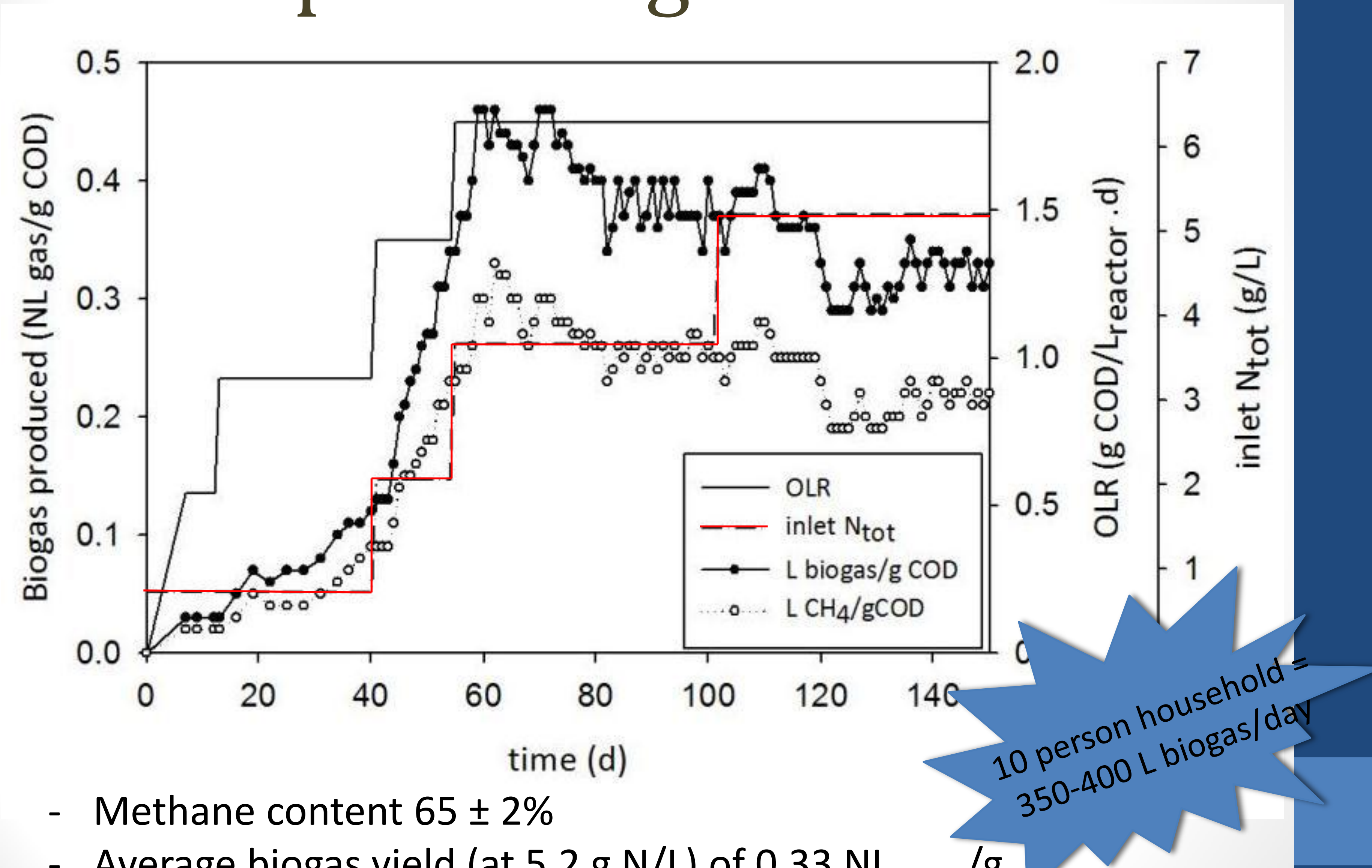


Anaerobic Digester

Anaerobic Digester Liquid Effluent



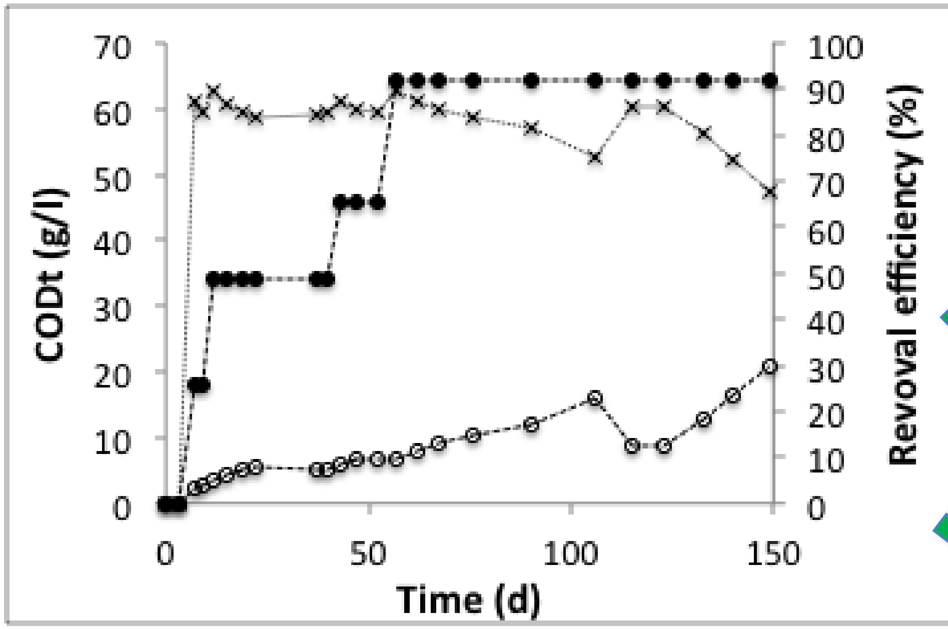
Startup and Biogas Production

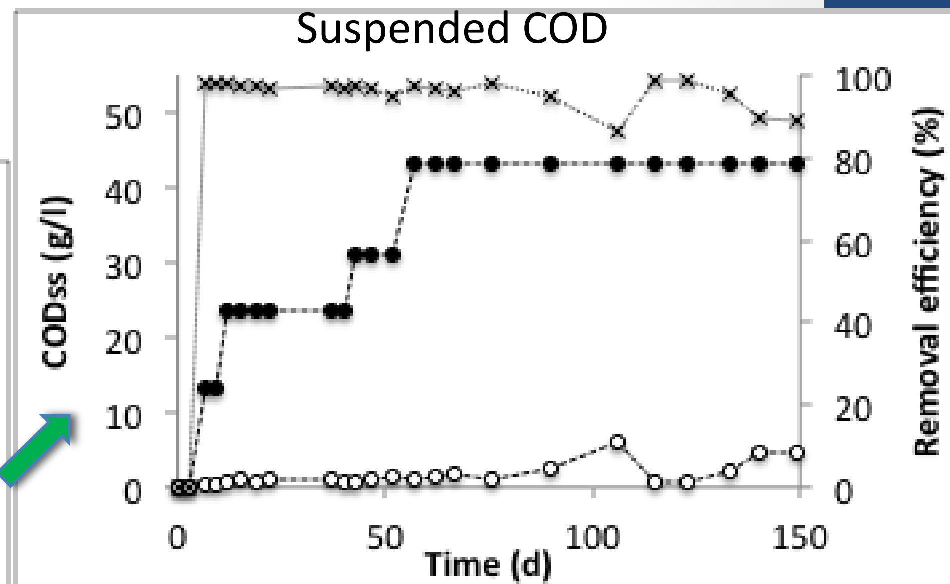


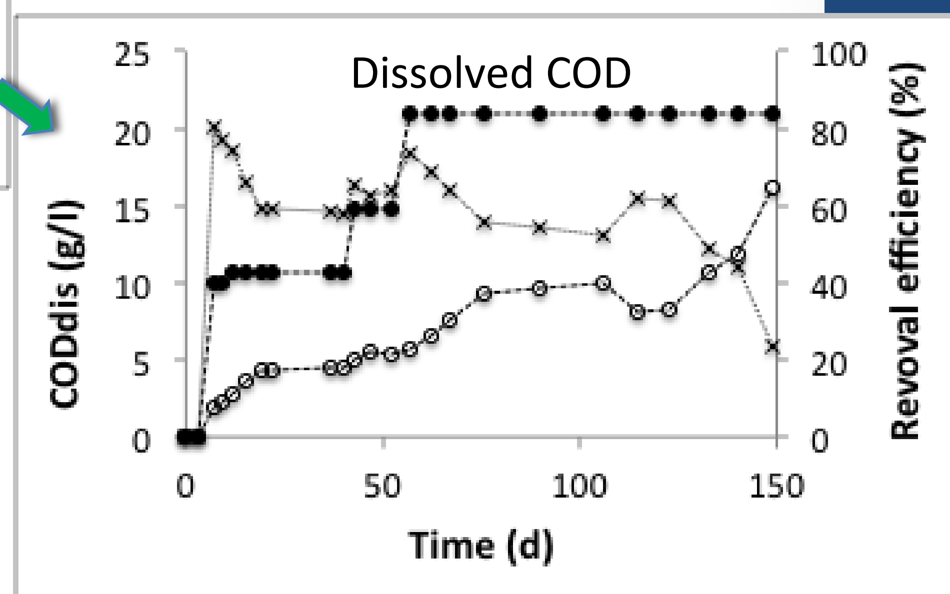
- Methane content 65 ± 2%
- Average biogas yield (at 5.2 g N/L) of 0.33 NL_{biogas}/g_{COD}
- Average biogas yield (at 3.6 g N/L) of 0.39 NL_{biogas}/g_{COD}

COD Removal Efficiency

Total COD







- Inlet concentration
- Outlet concentration
- Removal efficiency

Average removal efficiency ranges between 75-85 %.

Effect of N in the Feed

Data shows efficient anaerobic digestion using undiluted human excreta as feedstock, but...

Anaerobic digester conditions

"Better" working conditions

N_{in} ≤ 3.5 g N/L
Free ammonia < 75 mg/L
pH = 7 ± 0.1
$VFA_{acetate}$ < 2 $g_{acetate}$/L

Biogas yield ≈ 0.4 NL_{biogas}/g COD

Current operating conditions (day >100)

N_{in} = 5.2 g N/L
Free ammonia > 100 mg/L
pH = 7.7 ± 0.1
$VFA_{acetate}$ > 6 $g_{acetate}$/L

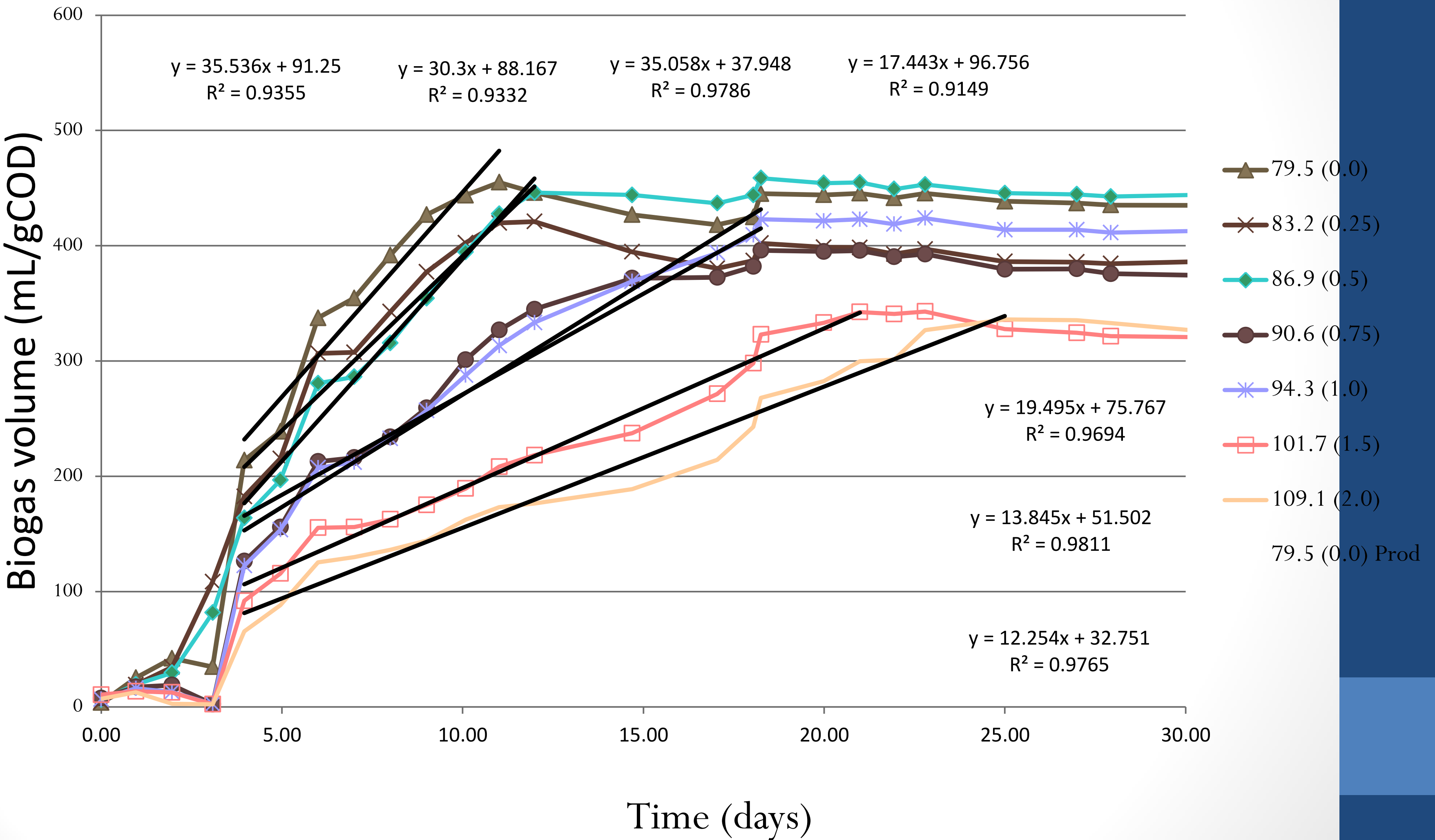
Biogas yield ≈ 0.3 NL_{biogas}/g COD

Acetate-utilizing methanogenic bacteria were primarily inhibited

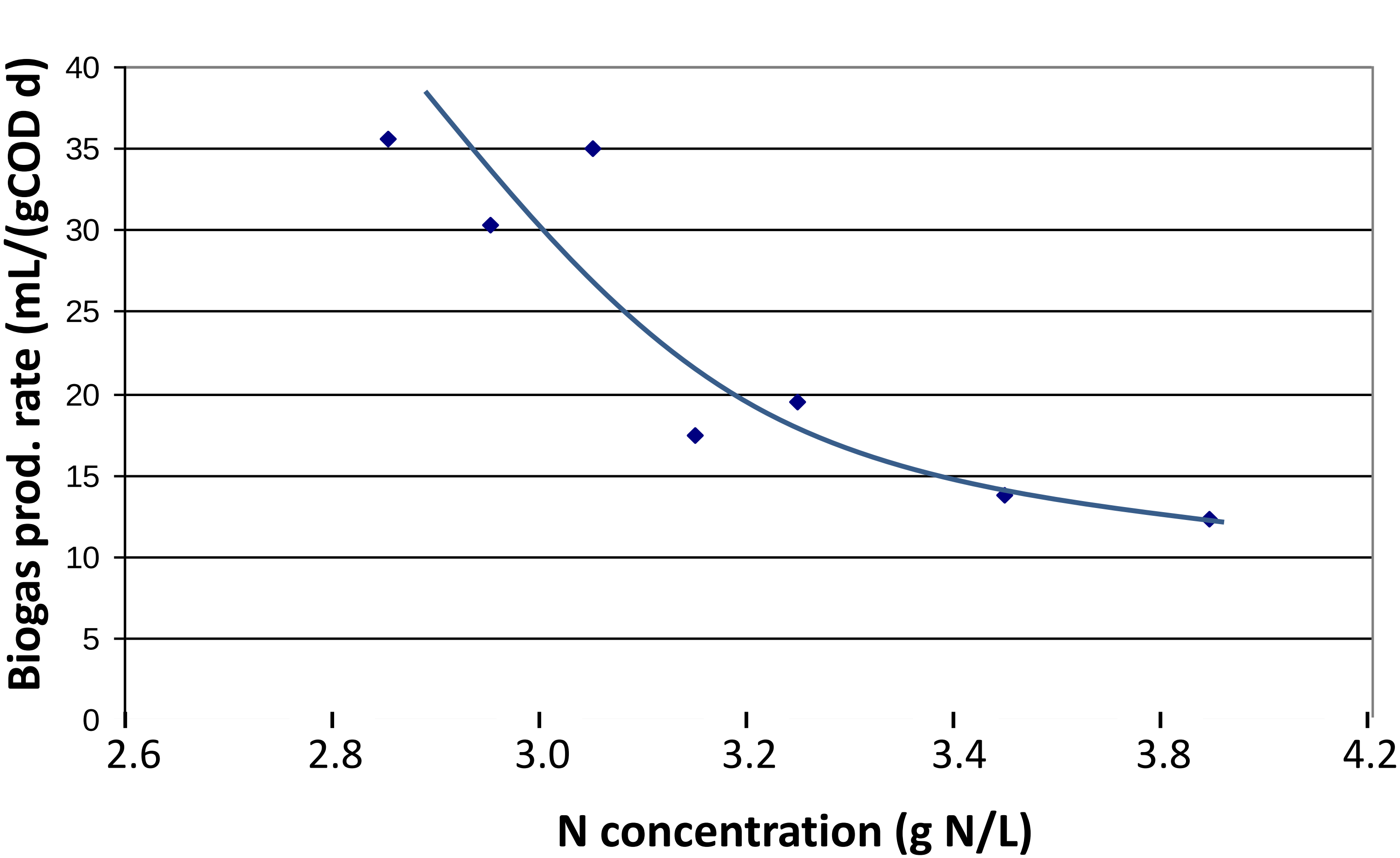
25 – 30 % inhibition

No more scum…

Effect of N on Biogas Potential

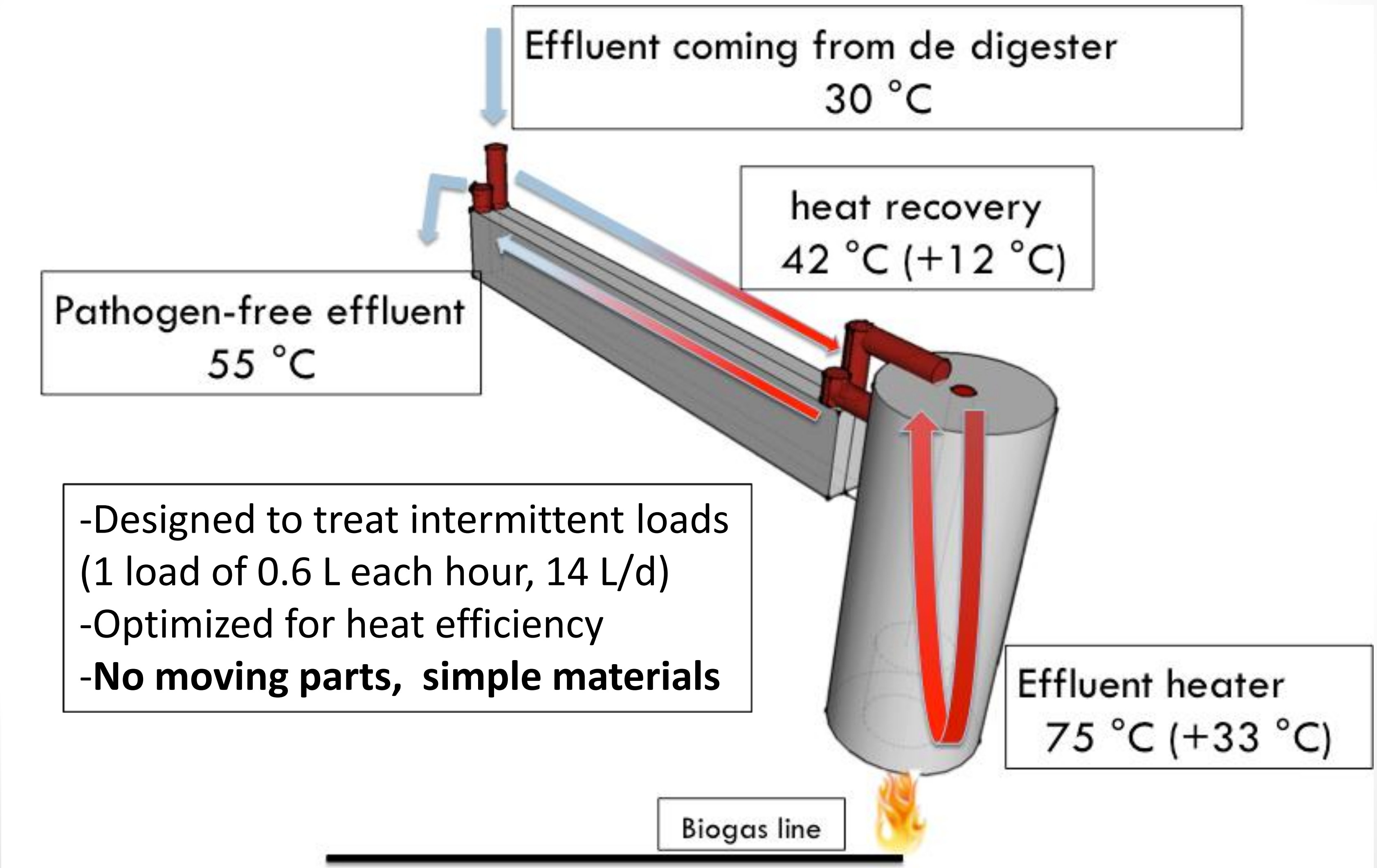


Effect of N on Biogas Production



-More testing is on-going (flasks and reactor)
-Effect of microorganism acclimation

Heat Sterilization System

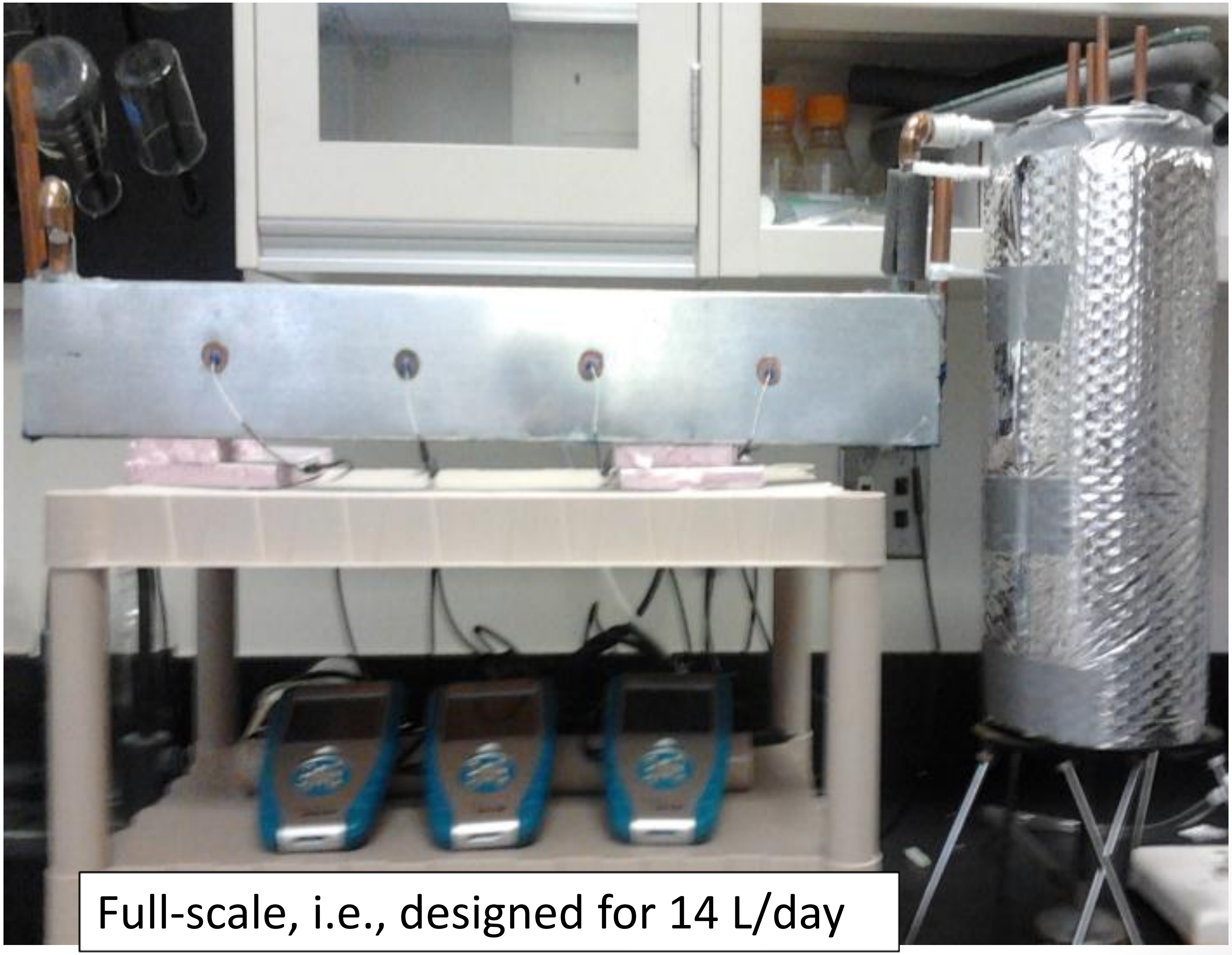


-Designed to treat intermittent loads (1 load of 0.6 L each hour, 14 L/d)

-Optimized for heat efficiency

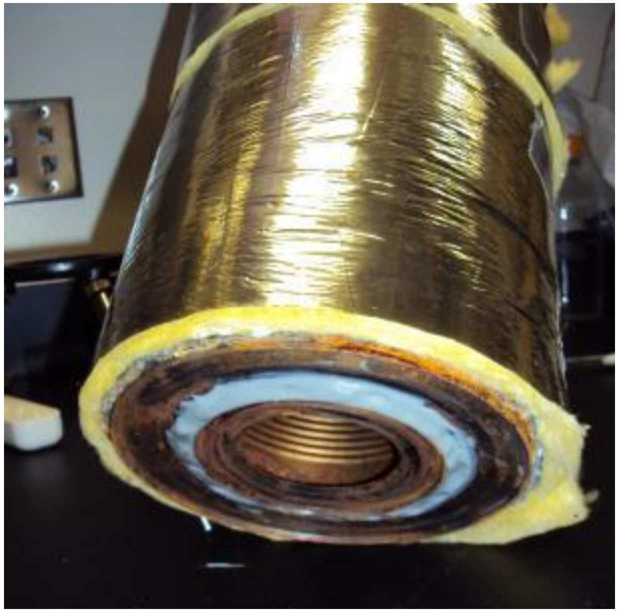
-**No moving parts, simple materials**

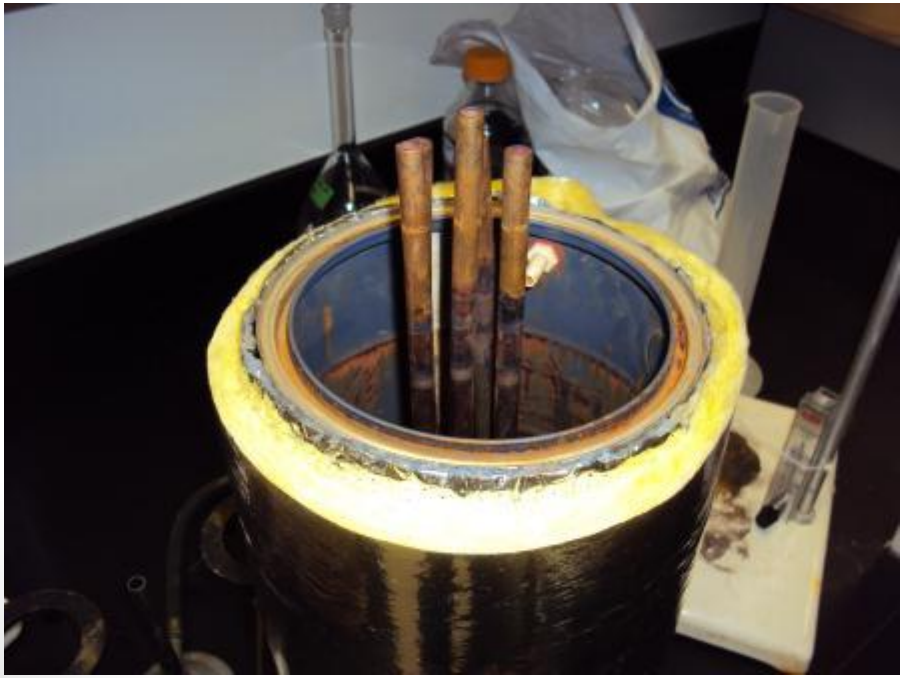
Heat Sterilization System



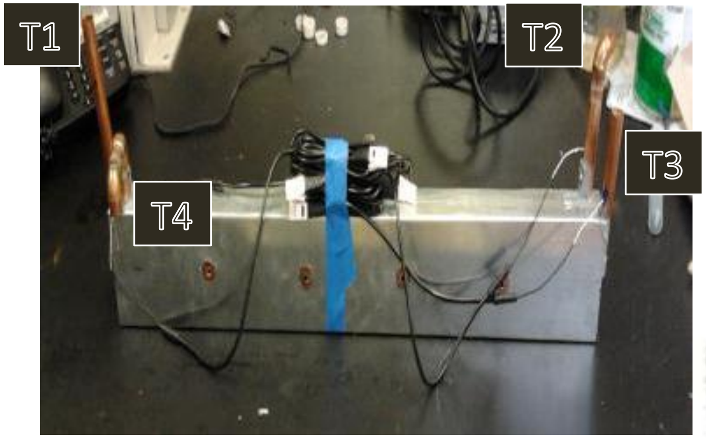
Full-scale, i.e., designed for 14 L/day

Heat Sterilization System

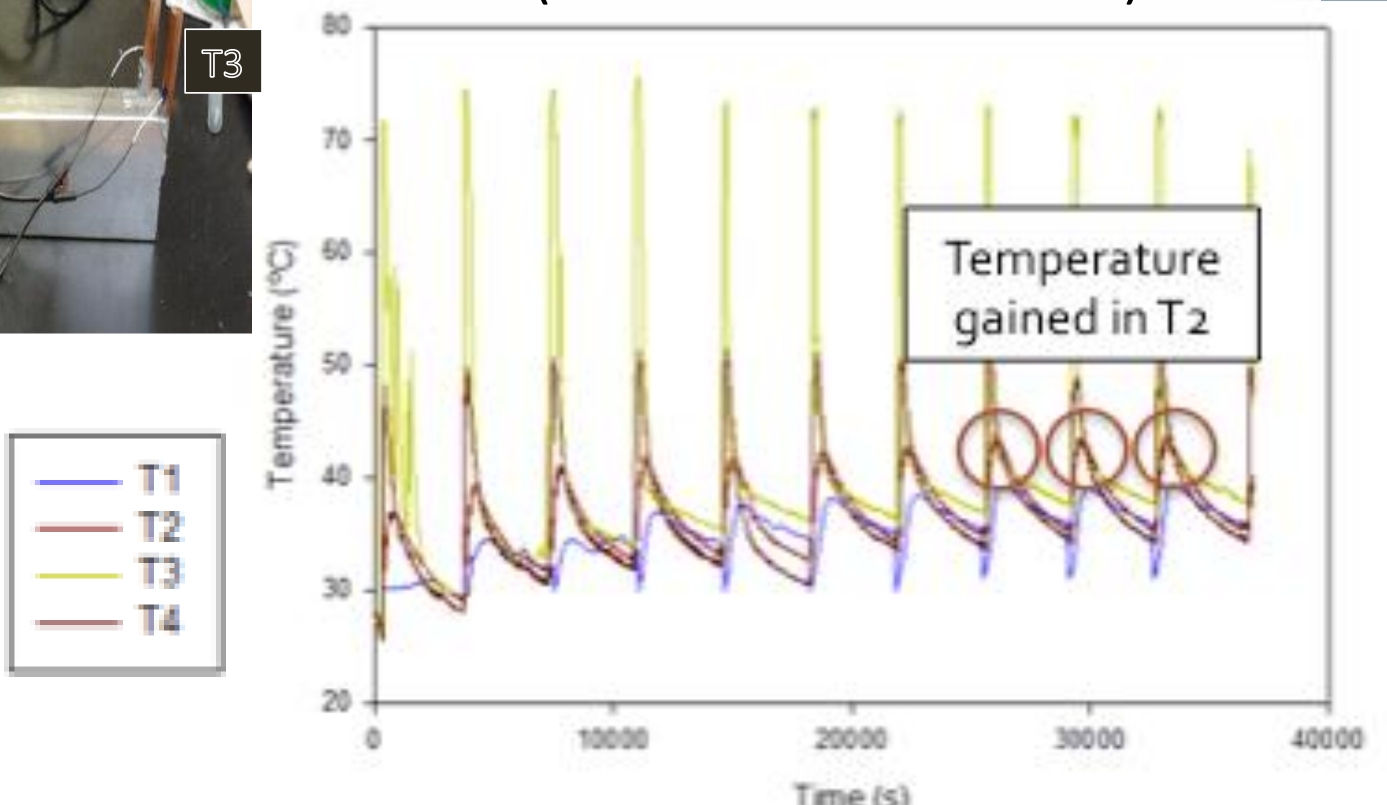




Heat Exchanger Performance

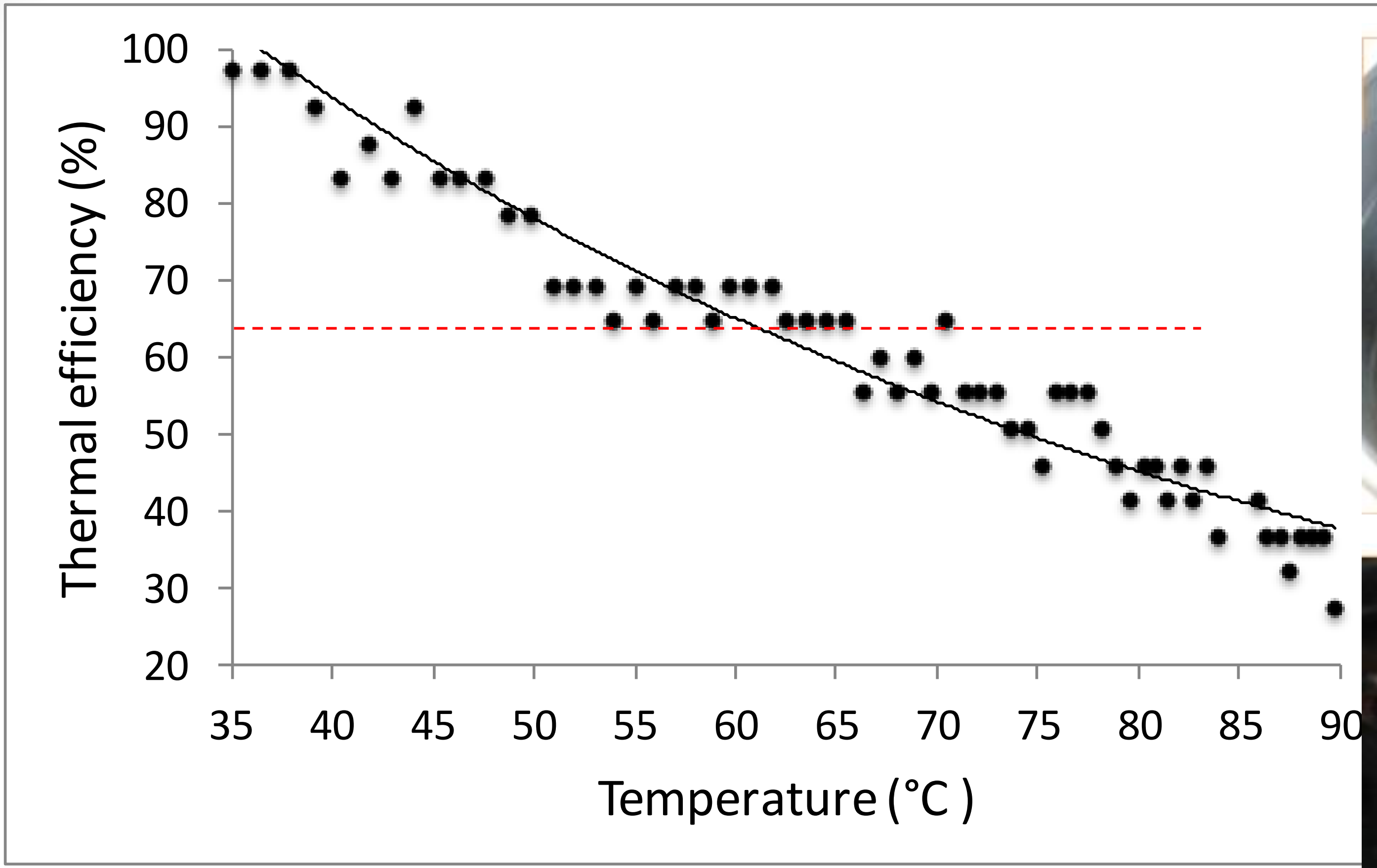


Intermittent operation: 600 mL each hour (each load fed in 5 min)



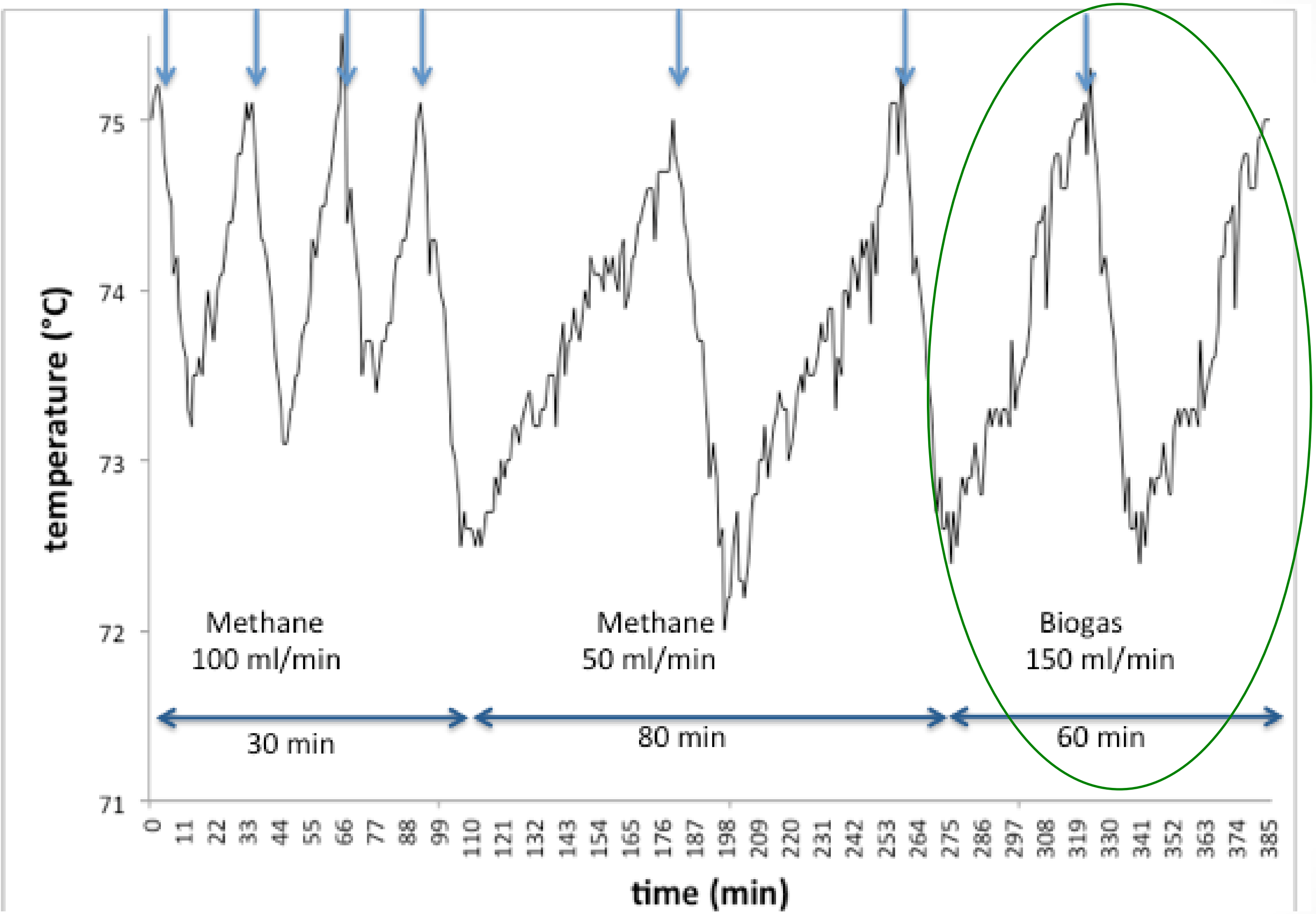
➡ Effluent stream is heated ~14 ºC before entering the heater thanks to the recovery in the heat exchanger

Thermal Efficiency of the Heater



Methane calorific value: 33.9 KJ/L
Temperature range: 55-75 °C
Thermal efficiency: 55-70 %

Heater Performance



230-280 L biogas per day will keep the heat-sterilization system at **75 °C** (**10 person-basis**). This is **65-75 % of the total biogas** produced in the anaerobic reactor.

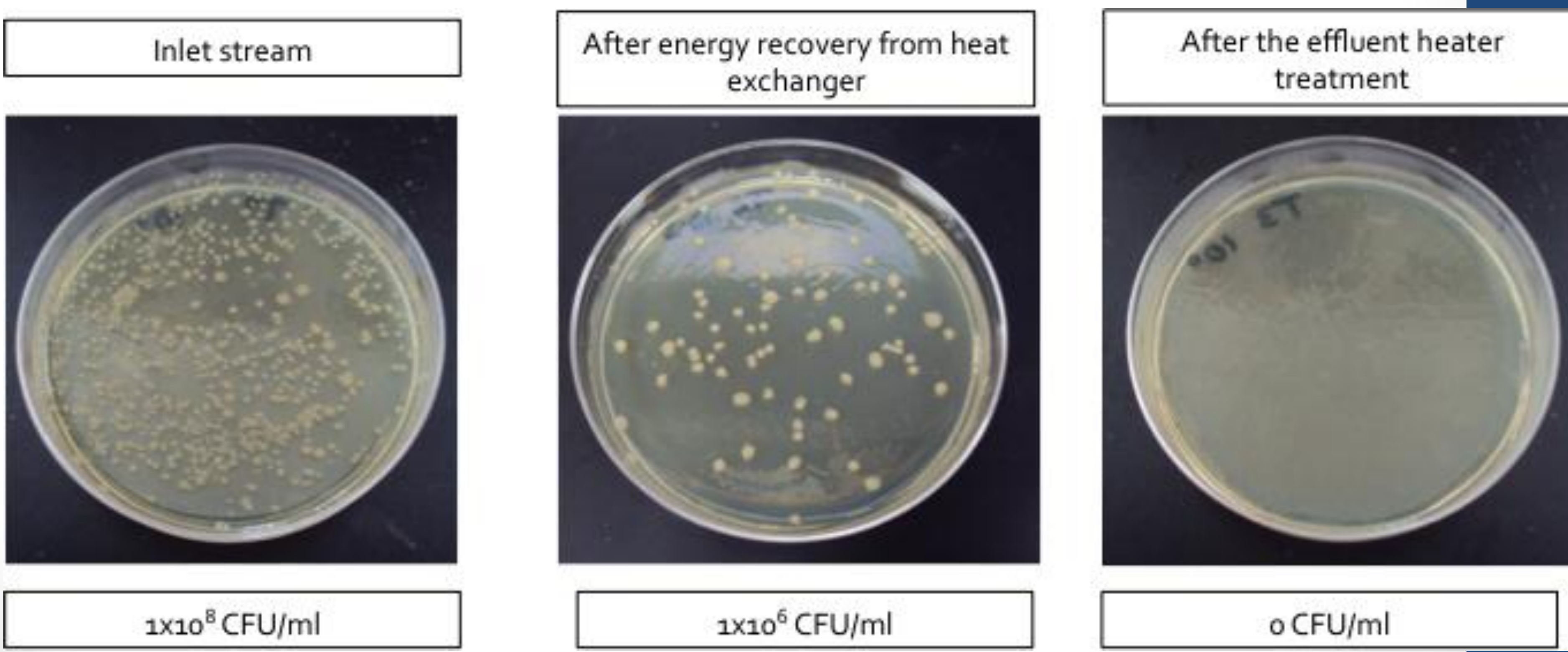
Heat Sterilization Tests

Approach:

-Test with *E. coli* (intermittent flow, 14 L/d in 0.6 L loads once per hour)

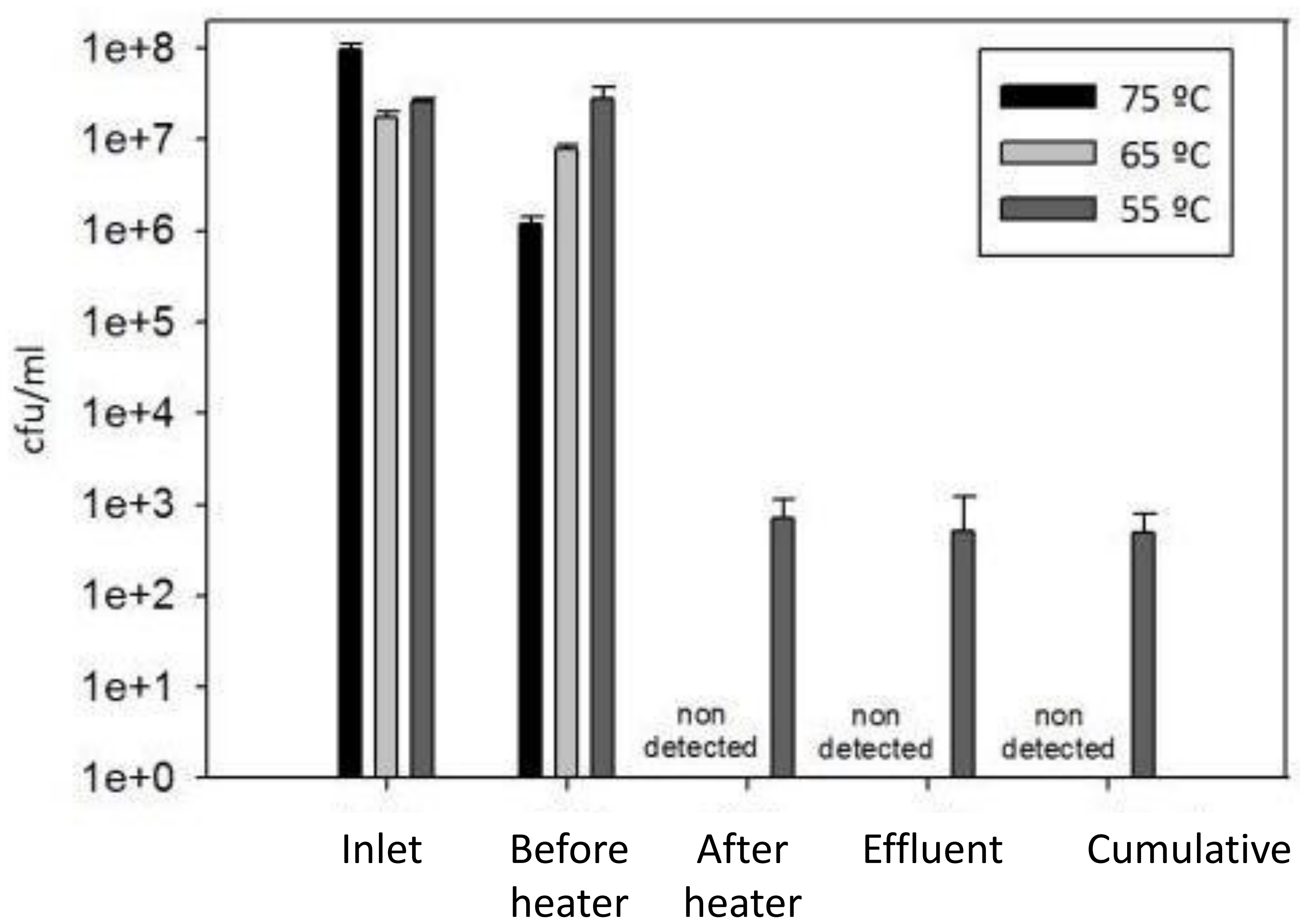
-Calibrate and validate flow, heat and heat deactivation model

-Simulate performance for helminth and virus*



*kill rate constants from Popat et al. Wat. Res. 2010, *44*, 5965-5972.

Heat Sterilization Tests



Conclusions

- Efficient anaerobic digestion was shown using undiluted human waste
- A yield ≈ 0.3-0.4 NL_{biogas}/g COD can be expected
- High ammonia concentrations cause inhibition (25-30 %) of acetate-utilizing methanogenic bacteria

- A simple biogas heater with an efficient heat recovery was designed and tested to heat-sterilize the treated sewage effluent
- 100 % of *E.coli* inactivation was achieved at a working T ≥ 65 °C.
- 4 log reductions were achieved with at a working T of 55 °C
- System was modeled (flow, heat transfer and pathogen disinfection)

- **The biogas produced during anaerobic digestion of undiluted human waste is enough to heat-sterilize the digester effluent stream**
- **System is simple (no moving parts)**
- **It reduces environmental footprint of sanitation (~7 tons CO_2eq. per system per year)**

Future Work

- Build a new heat exchanger (tube and shell)
- Value engineer system: passive solar, simple thermostat …
- Build a full-scale prototype for demonstration (now)
  - US-based testing and debugging (early 2013)
  - Build on / team-up with on-going health studies for demonstrations in suitable locations (Peru, Uganda, Zambia, Malawi, …) in 2013.
  - Challenges for assessing field studies: randomized controlled trials, define intermediate outcomes (and more)
- Small co-gen heat and power biogas generator to be designed and built by Duke ME students (Winter 2013)

Acknowledgments: Bill & Melinda Gates Foundation

Contact: marc.deshusses@duke.edu

http://deshusses.pratt.duke.edu/

Backup slides

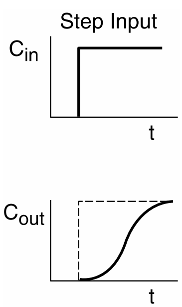
Heat-sterilization system

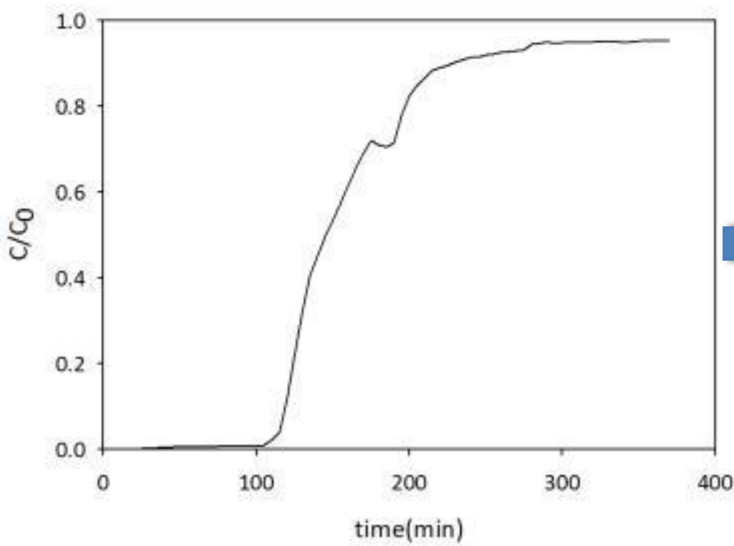
HEAT EXCHANGER

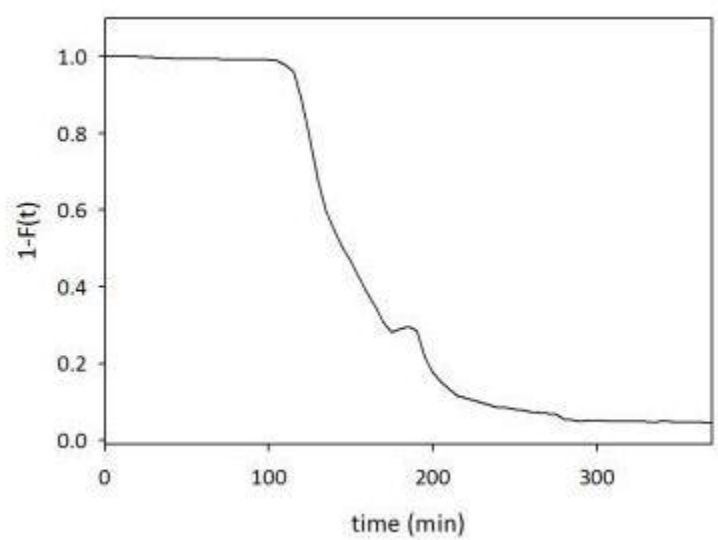
Residence time distribution (RTD) – step process

$$F(t) = \left[\frac{C_{out}}{C_0}\right]_{step}$$

$$\tau = \int_0^{\infty} [1 - F(t)]\, dt$$

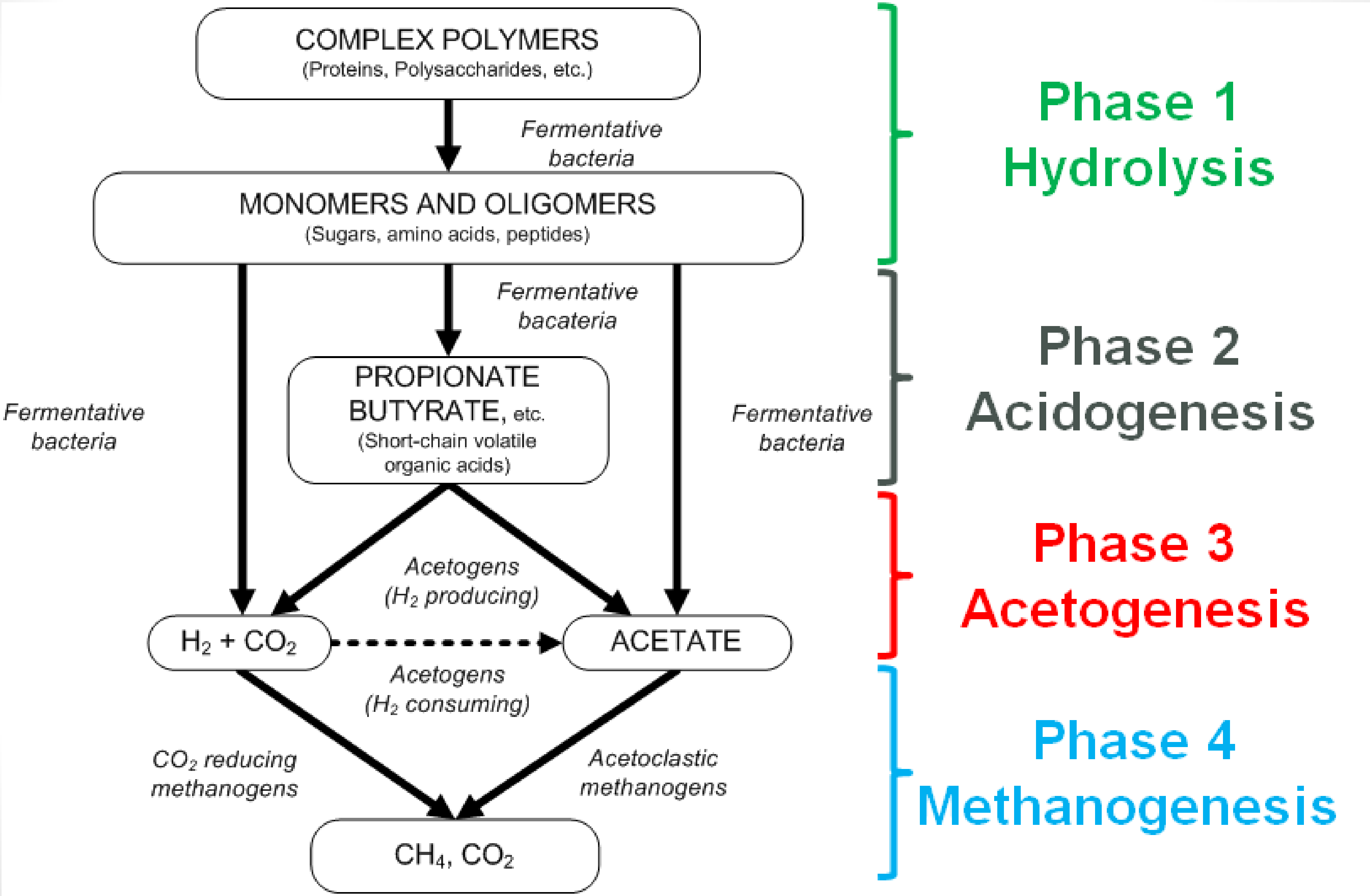






Volume: 1650 ml
Flowrate: 600 ml/h
Mean residence time: 166 min
Theoretical mean residence time: 165 min

Anaerobic Digestion 101



Source: Syed Hashsham, PhD, lecture notes, Michigan State University

Pig waste to energy… optimizing performance and environmental benefits of anaerobic digestion