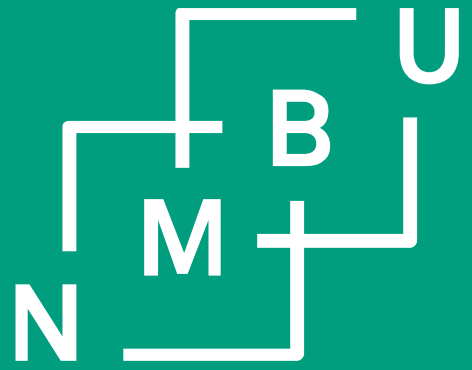

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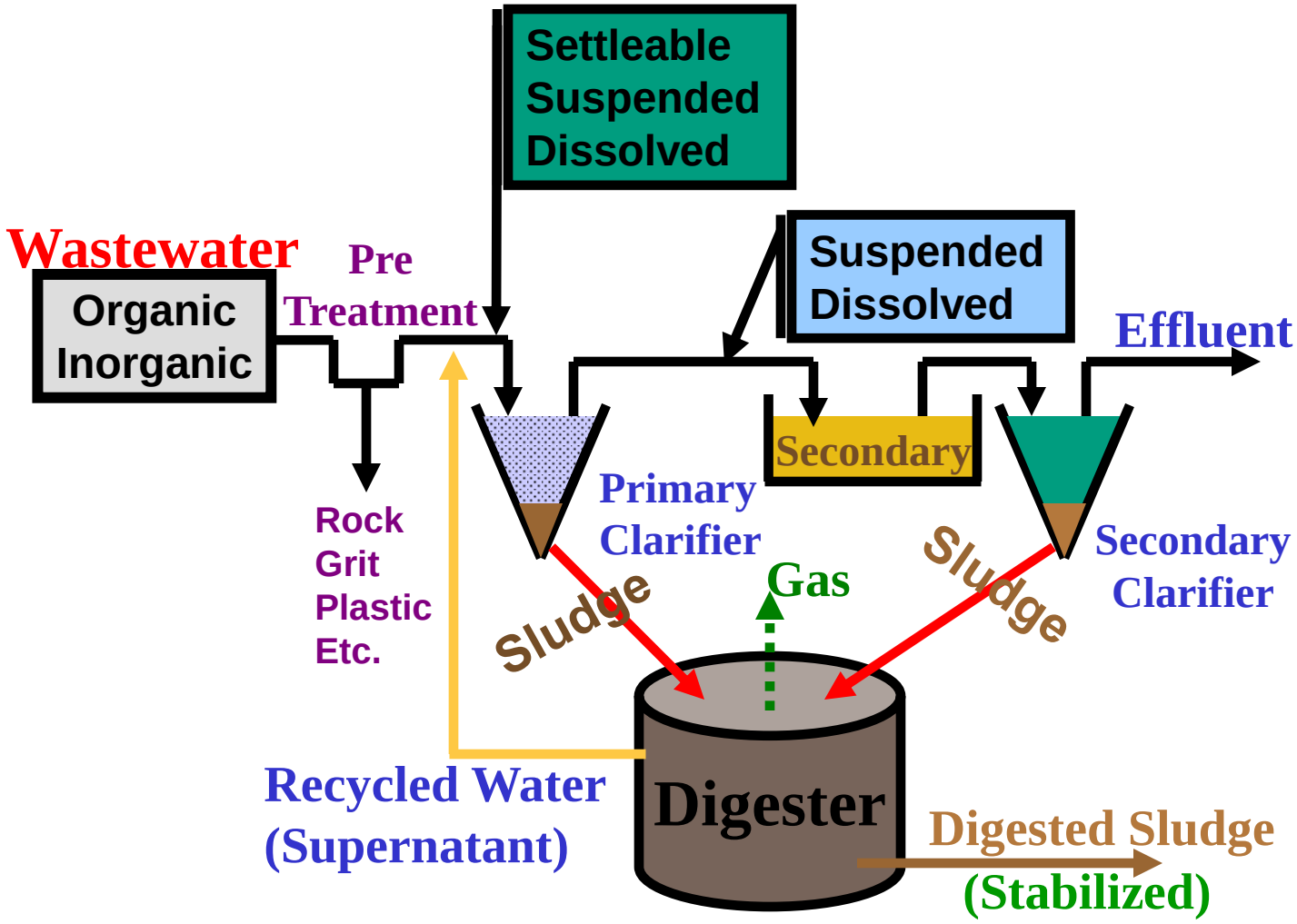
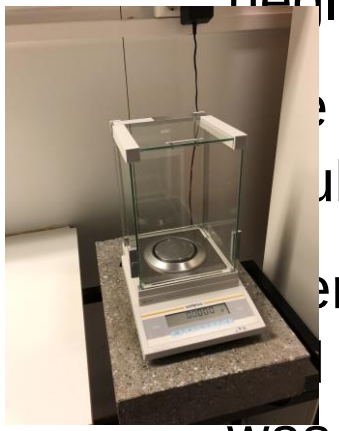
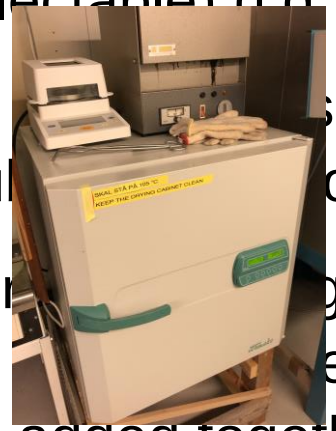

Settleable
Suspended
Dissolved
Suspended
Dissolved
Wastewater
Organic
Inorganic
Pre
Treatment
Effluent
Secondary
Rock
Grit
Plastic
Etc.
Primary
Clarifier
Sludge
Gas
Sludge
Secondary
Clarifier
Recycled Water
(Supernatant)
Digester
Digested Sludge
(Stabilized)

Preparation of substrate for the test

- We have a protocol. When using 1125 ml bottles
  - Inoculums: 150 ml and fill with 450 ml water (taken from an operating reactor, and run until the biogas production is neglectable) (i.g. 14 days)


aced in the
s for ripening.
were opened
wo gram VS,
was added together with water up to a total mass of 100 g.
  - VS: d.m. (105 C) minus ash (550 C)

Measuring gas production:

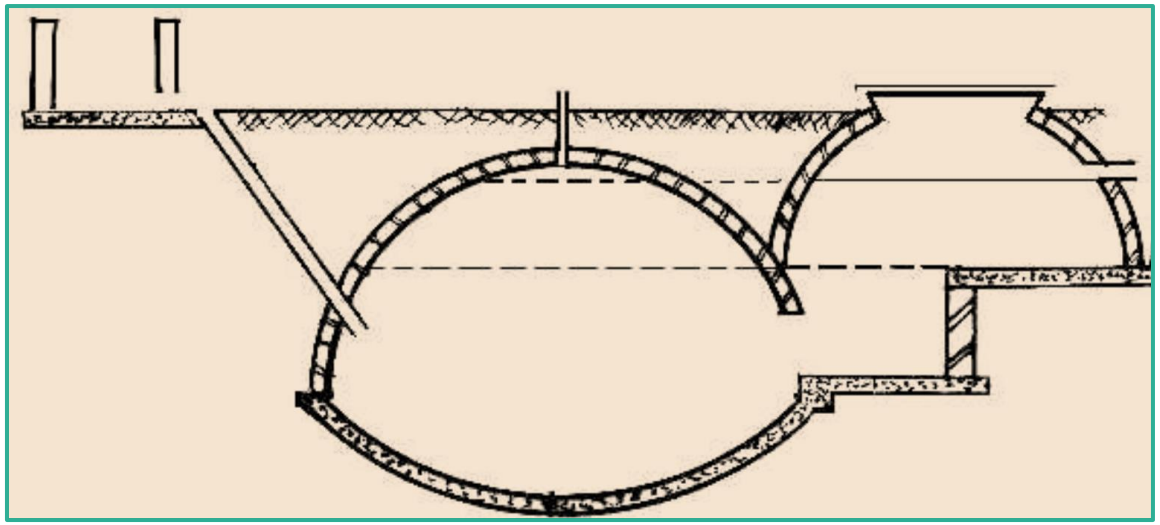
- 1. Headspace: weighing the bottles: full minus emty. Assuming that the specific weight of samples, water and inoculums are 1 kg/L.

$$Vb = \frac{n \times R \times 273}{Po} = \left(\frac{dP \times V}{R \times T}\right) \times \left(\frac{R \times 273}{Po}\right) = \frac{dP \times V \times 273}{T \times Po}$$

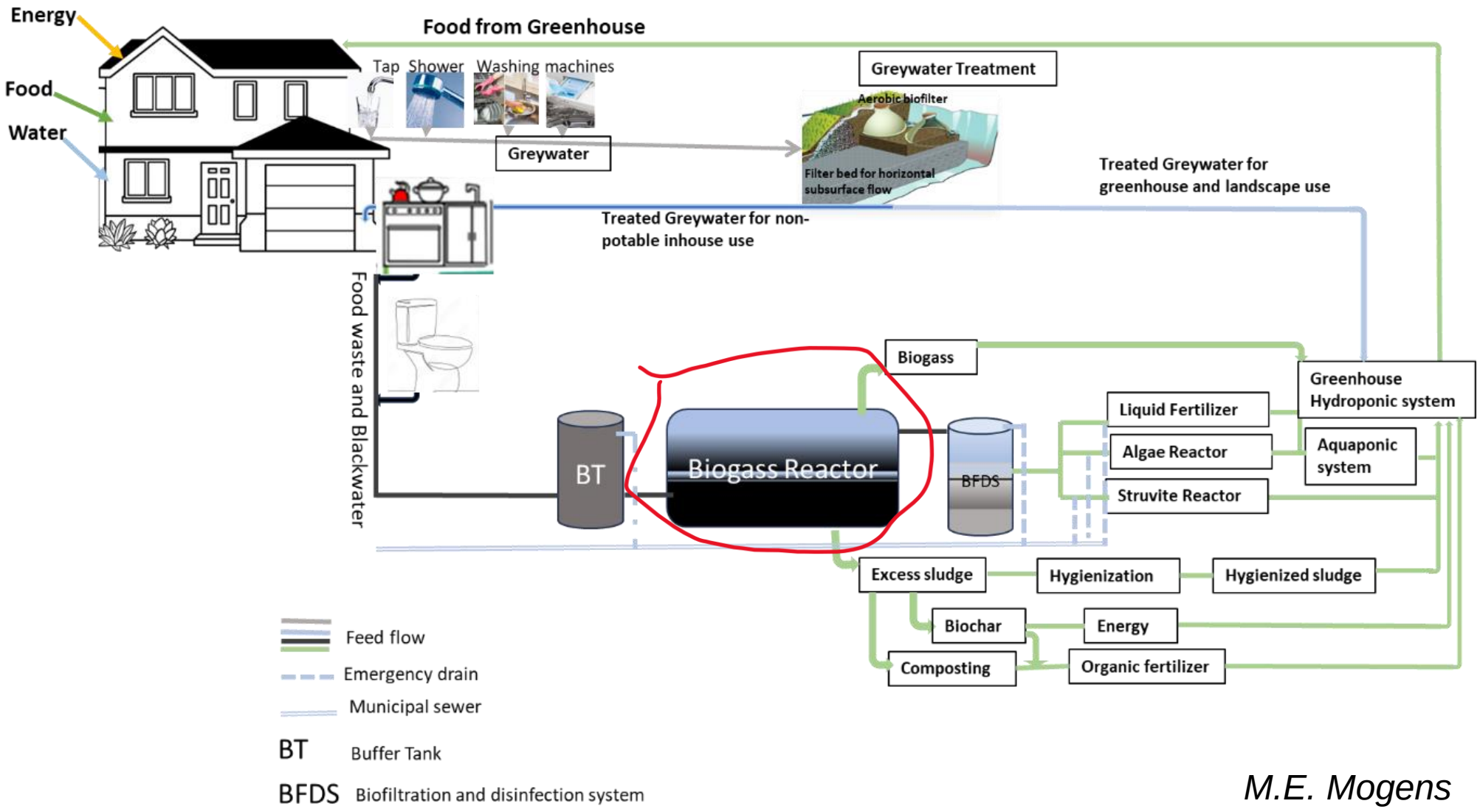
- Using pressure meter and $pV = nRT$.

V_b Volume of biogas
273 is 0 C temp, and the production is corrected to STP
R is the gas constant
dP = over pressure from the instrument
T is the temperature in the incubator room (37 C, 310 K)
V volume of headspace
P_0 = 1 bar (1013 mbar)

Anaerobic digester – Biogas settler (BS)



- Demonstrating project - SiEuGreen



M.E. Mogens

The biological process

1. Hydrolysis of carbohydrate, protein and fat into smaller molecules. Enzyme process (bacterial produced enzymes)
2. Fermenting bacteria. Results in hydrogen, carbon dioxide, acetate, alcohol.
   a) Acidogonesis (organic acids)
   b) Acetogonesis
3. Methanogenis. Archae producing methane from hydrogen and carbon dioxide or acetate
   1. Depending on pH
   2. Ammonia-content

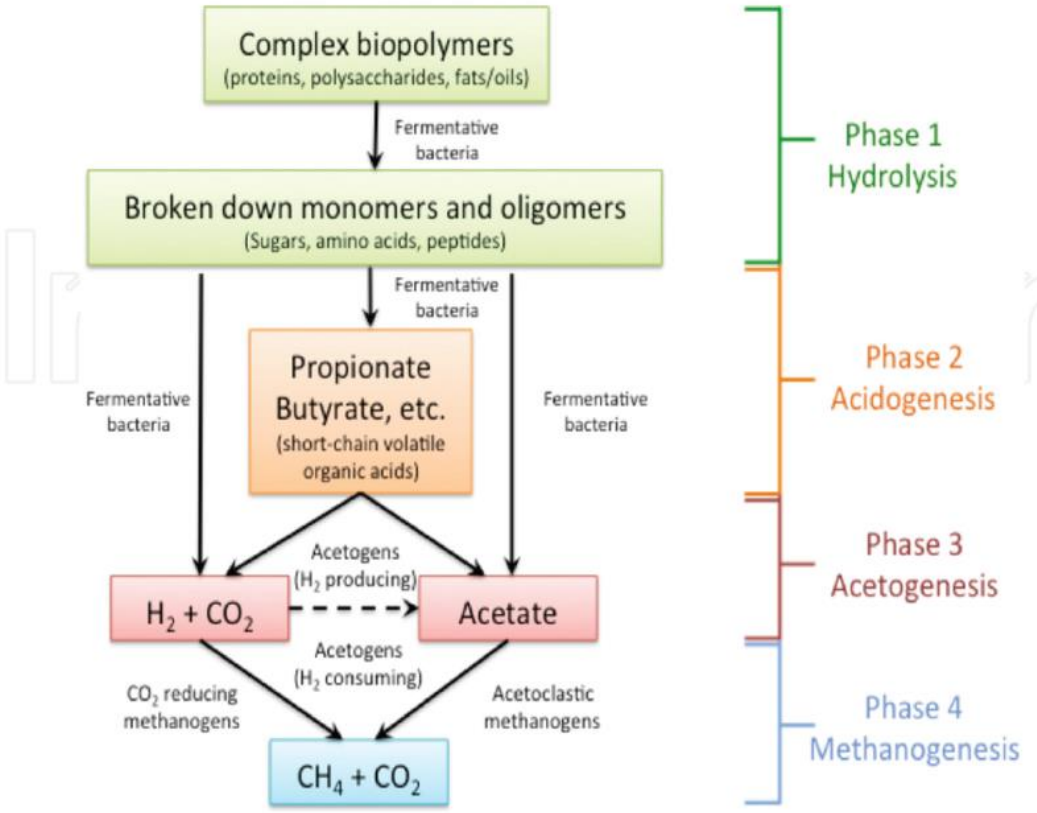


Figure 1.
Schematic representation of anaerobic digestion (source: https://www.e-education.psu.edu/egee439).

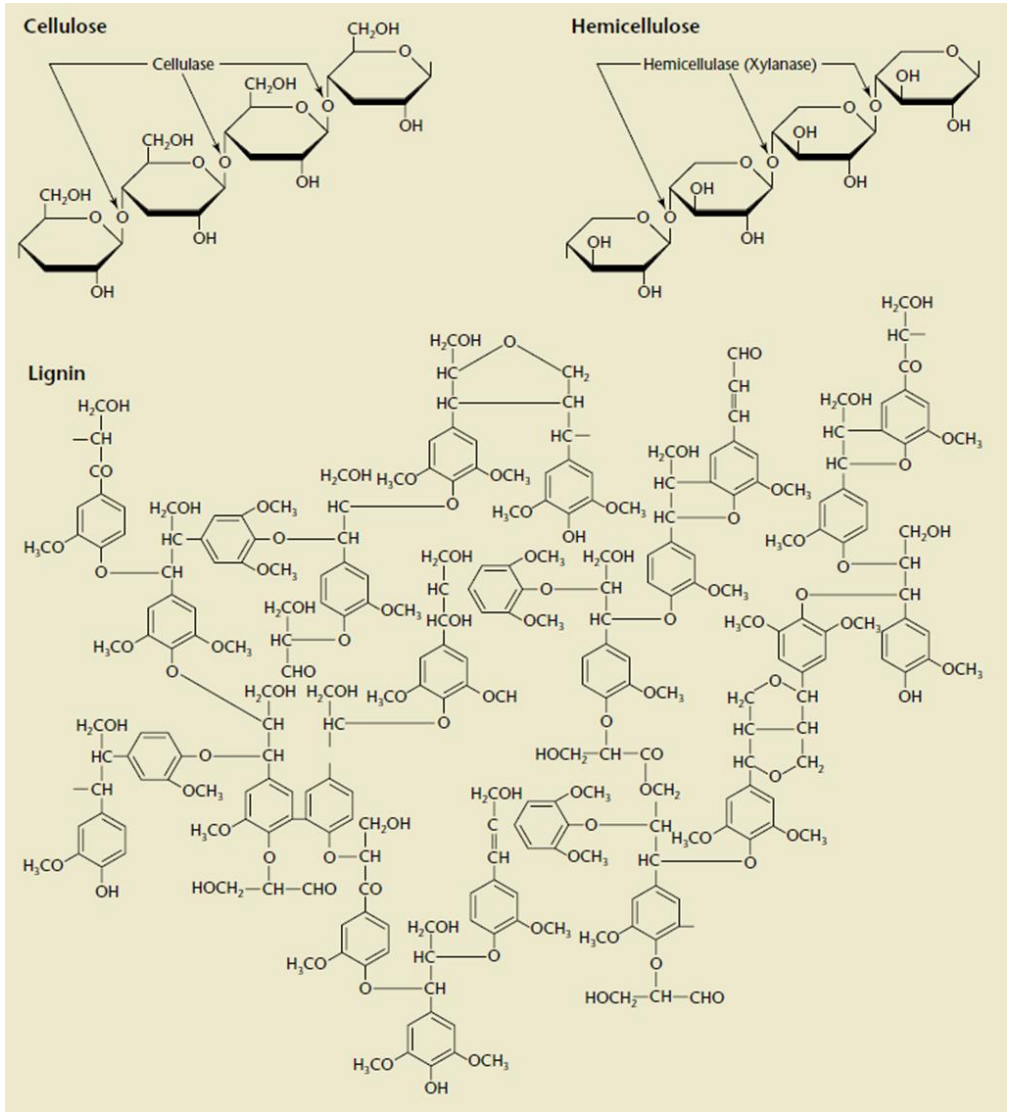
Reduction of DM (biogas) – not total mass

Hydrolysis – enzymatic process

Enzymes	Substrate	Breakdown products
Proteinase	Proteins	Amino acids
Cellulase	Cellulose	Cellobiose and glucose
Hemicellulase	Hemicellulose	Sugars, such as glucose, xylose, mannose and arabinose
Amylase	Starch	Glucose
Lipase	Fats	Fatty acids and glycerol
Pectinase	Pectin	Sugars, such as galactose and arabinose, and polygalactic uronic acid

Table 3. Some important groups of hydrolytic enzymes and their functions.

Enzyme process



How to calculate biogas potential?

1. Buswell (1952):

$$C_cH_hO_oN_nS_s + 1/4(4c - h - 2o + 3n + 2s)H_2O \rightarrow 1/8(4c - h + 2o + 3n + 2s)CO_2 + 1/8(4c + h - 2o - 3n - 2s)CH_4 + nNH_3 + sH_2S$$

Table 9.4.3 Theoretical methane yield for a number of organic compounds.

Substrate	Composition	CH_4 yield (STP l/g VS)	CH_4 yield (STP l/g COD)	CH_4 (%)
Carbohydrate	$(C_6H_{10}O_5)_n$	0.415	0.35	50
Protein[a]	$C_5H_7NO_2$	0.496	0.35	50
Lipids	$C_{57}H_{104}O_6$	1.014	0.35	70
Ethanol	C_2H_6O	0.730	0.35	75
Acetate	$C_2H_4O_2$	0.373	0.35	50
Propionate	$C_3H_6O_2$	0.530	0.35	58

[a] Nitrogen is converted to NH_3

1. Difficulties:
   a) A part will be used for growing of microorg. (5-10%)
   b) Some will be lost via outflow (~10%)
   c) Lignin part of carbohydrates is not available for degradation
   d) Retention time
   e) C/N, inhibitors (ammonia), organic loading rate, co-substrates
   f) Availability of nutrients

Biogas - COD

Standard temperature and pressure – STP. Sometimes also called Normal condition i.g. Nm^3
Dry matter – t.s.
Volatile solids – VS
Chemical oxygen demand – COD
Volatile fatty acids – VFA
Biomethane potential – BMP
Spesific biogas/methane potential – l gas/g VS

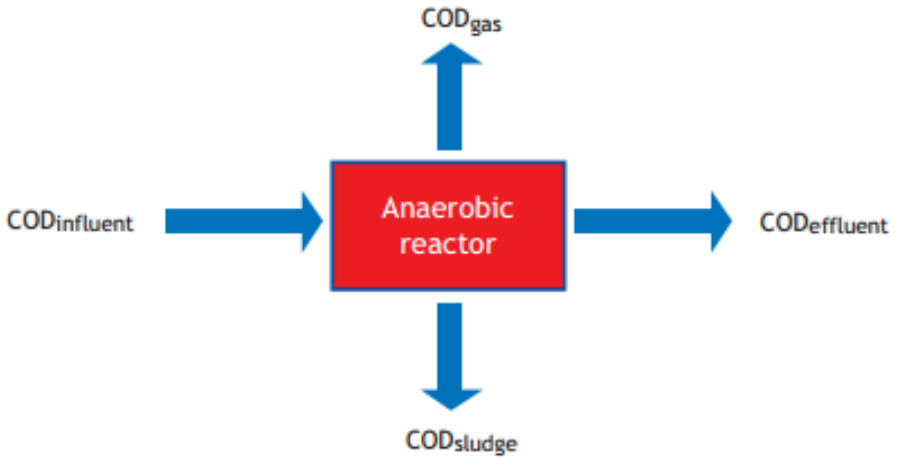


Figure 16.12 COD balance of an anaerobic reactor. By differentiating the COD fractions of gas, liquid and solids, the missing parameters can be estimated from the more easily measurable parameters

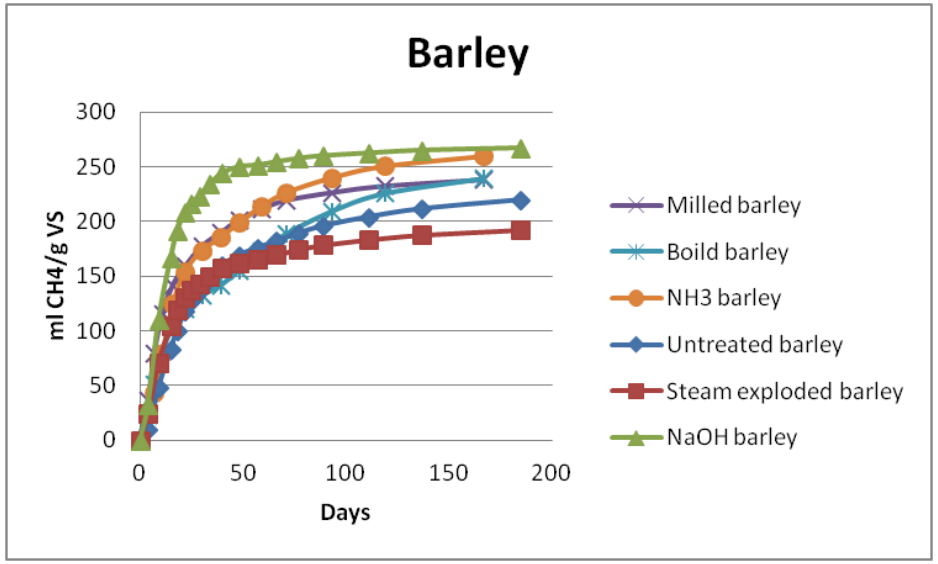
Based on the basic influent characteristics, i.e. flow rate and COD concentrations, and information on the biodegradability of the COD, the expected CH_4 production rate can be easily estimated. From section 16.3.1. we can derive that:

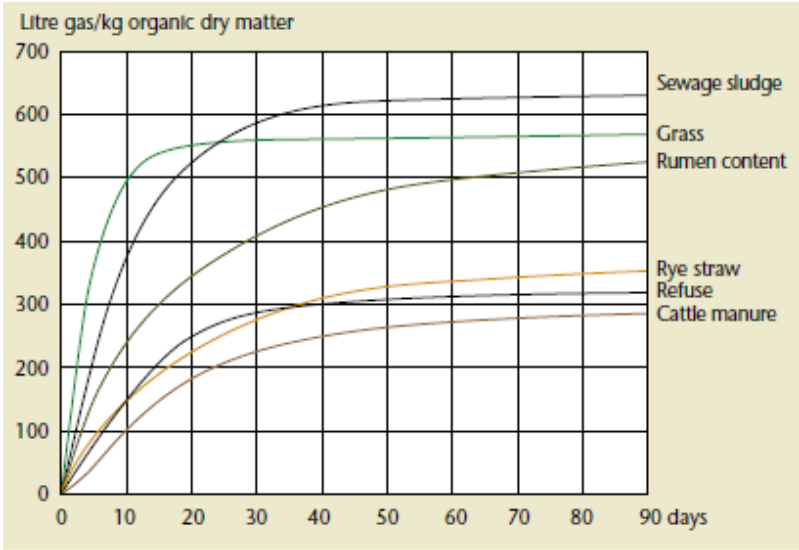
$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2H_2O \qquad (16.45)$$

which means that 22.4 m^3 CH_4 (STP) requires 2 moles of O_2 (COD), which equals 64 kg COD. Therefore, theoretically, 1 kg COD can be converted in 0.35 m^3 CH_4.

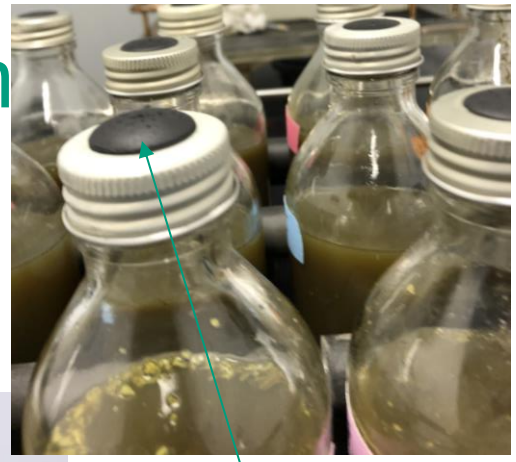
Potential studies (batch)

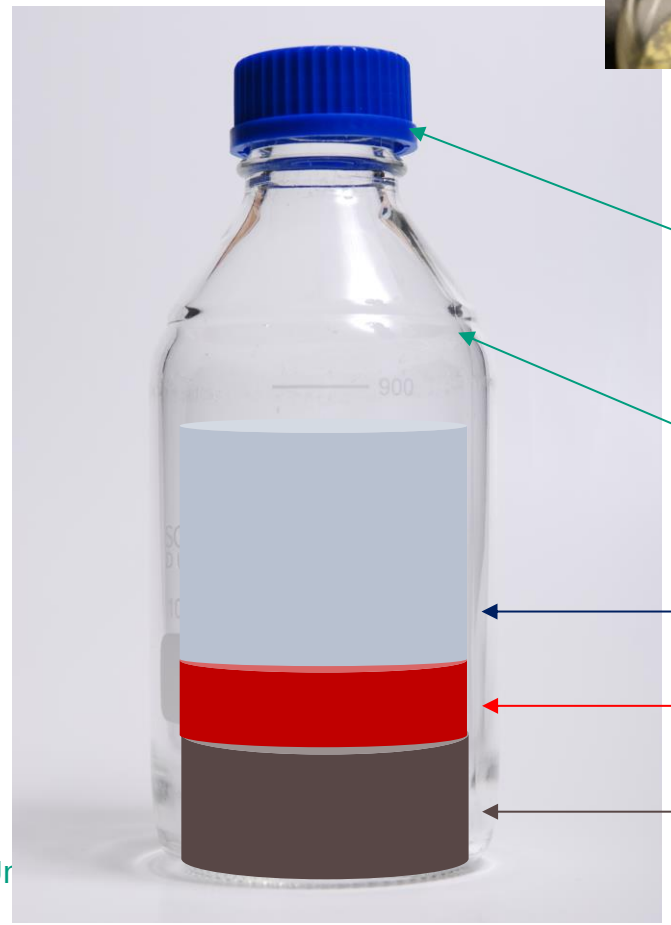
Manometric biogas potential determination





BMP - biometh potential





Rubber stoppers

Headspace

Water

Sample (substate)

Inoculums

Result …

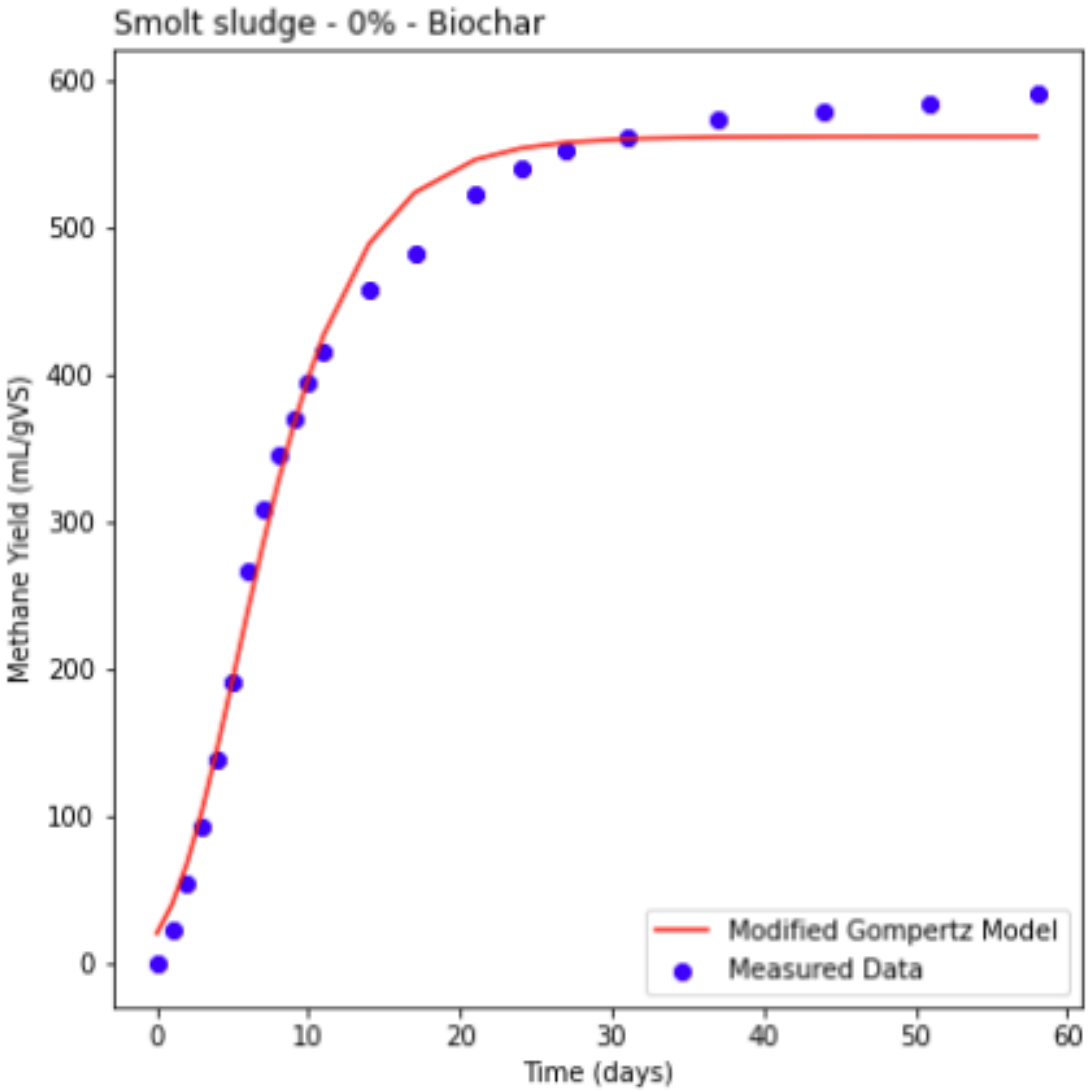


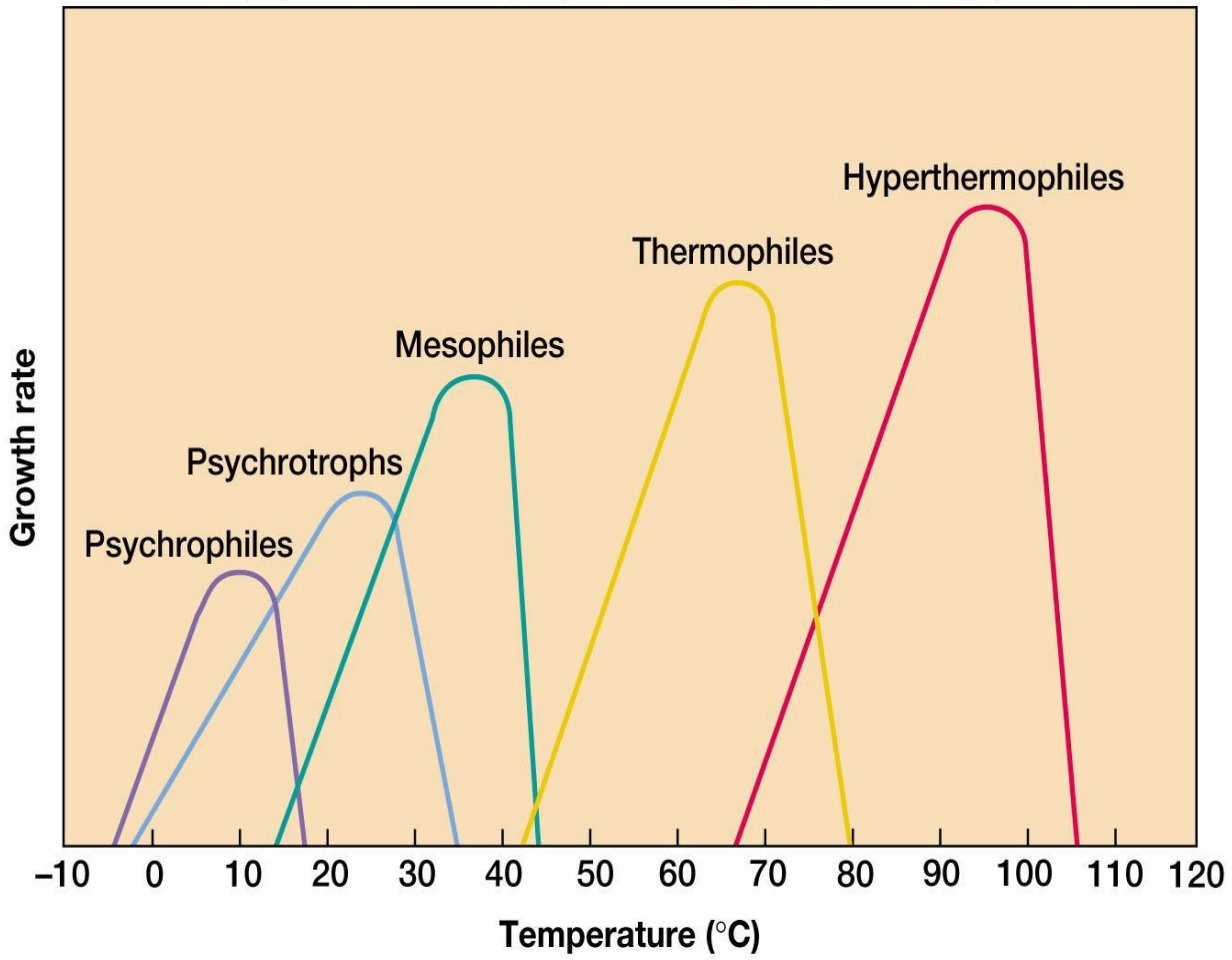
TABLE 6.2
Methane Potential of Some Organic Waste

Waste	Methane Yield ($m^3 CH_4 kg^{-1}$ VS)	References
Industrial and commercial waste		
Expired food	0.47–1.10	Braun et al. (2003)
Sludge from distilleries	0.40–0.47	Braun et al. (2003)
Potato waste	0.69–0.89	Braun et al. (2003)
Molasses	0.31	Angelidaki and Ellegaard (2003)
Edible oil sludge	1.10	Braun et al. (2003)
Municipal waste		
Household waste	0.40–0.50	Angelidaki and Ellegaard (2003)
Garden waste	0.10–0.20	Angelidaki and Ellegaard (2003)
Paper	0.08–0.37	Owens and Chynoweth (1993)
Market waste	0.90	Braun et al. (2003)
Municipal solid waste	0.20–0.22	Chynoweth et al. (1993)
Banana peel	0.27–0.32	Gunaseelan (2004)
Citrus waste	0.43–0.73	Gunaseelan (2004)
Vegetable waste	0.19–0.40	Gunaseelan (2004)
Animal and slaughterhouse waste		
Animal fat	1.00	Braun et al. (2003)
Stomach and gut contents	0.4–0.46	Ahring et al. (1992)
Rumen content	0.35	Braun et al. (2003)
Blood	0.65	Braun et al. (2003)
Agricultural waste		
Cow manure	0.15–0.30	Angelidaki and Ellegaard (2003)
Swine manure	0.30–0.51	Ahring et al. (1992); Møller et al. (2004)
Poultry manure	0.30	Ahring et al. (1992)
Straw and other plant residues	0.15–0.36	Angelidaki and Ellegaard (2003); Møller et al. (2004)
Green plant, crops, grain	0.18–0.28	Angelidaki and Ellegaard (2003)
Sugarcane	0.23–0.30	Chynoweth et al. (1993)
Sorghum	0.26–0.39	Chynoweth et al. (1993)

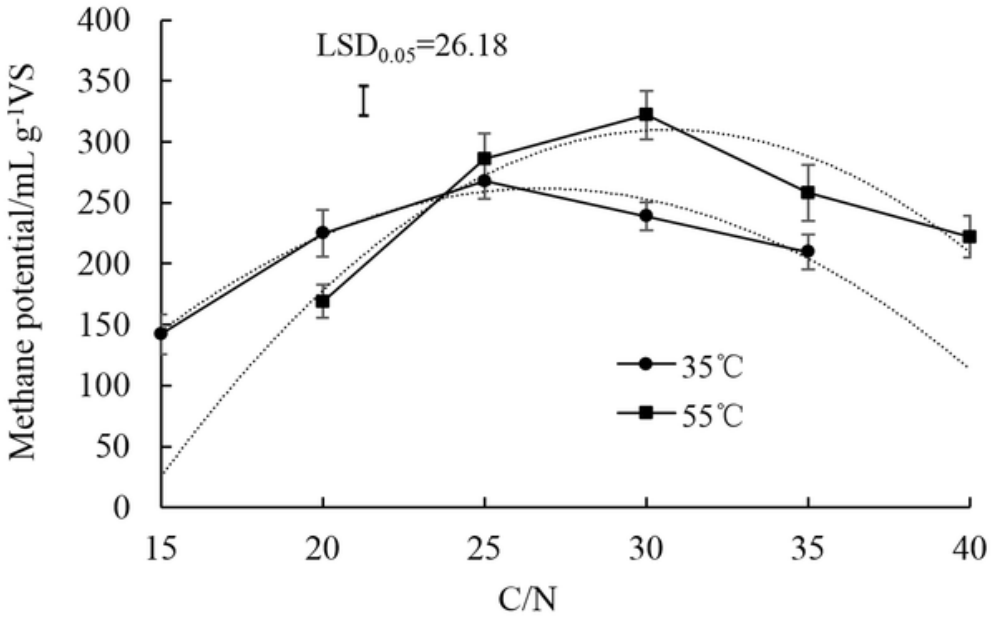
Factors that can affect the complex system of AD

- The rate and efficiency of anaerobic digestion process is controlled by:
- Type of waste being digested
  - Pre-treatment
- Process temperature
  - Psychrophilic, Mesophilic, thermophilic
- The presence of toxic materials
- The pH and alkalinity
- Inhibiting material
  - Ammonia, VFA
- The hydraulic retention time
- The organic loading rate

Temperature and growth rate



C/N-ratio



Wang X, Lu X, Li F, Yang G (2014) Effects of Temperature and Carbon-Nitrogen (C/N) Ratio on the Performance of Anaerobic Co-Digestion of Dairy Manure, Chicken Manure and Rice Straw: Focusing on Ammonia Inhibition. PLoS ONE 9(5): e97265. doi:10.1371/journal.pone.0097265

Material	C/N- ratio
Cattle manure-liquid	6 - 20
Chicken manure	3 - 10
Swine manure-liquid	5 - 15
Straw	50 - 150
Horse manure	20 - 25
Grass	12 - 26
Potatoes	35 - 60
Sugar beet/beet foliage	35 - 46/14
Cereals	16 - 40
Fruits and vegetables	7 - 35
Mixed food waste	15 - 32
Slaughterhouse waste-soft tissue	4
Slaughterhouse waste –guts	22 - 37
Food waste	3 - 17
Distillery waste	8

Ammonia (NH_3)

- Degradiation of proteins (hydrolyse to amino acids, and then degraded to VFA and ammonia in the acidogonesis)
- Measured as ammonium, > 3g/l could result in inhibition
- Hydrogenotophs tolerate higher concentrations

Free ammonia is calculated as:

$$NH_3 = NH_4\left(1 + \frac{10^{-pH}}{10^{-\left(0.09018 + \frac{2729.92}{T}\right)}}\right)$$

where NH_4 is the total ammonia nitrogen and T is temperature expressed in Kelvin.

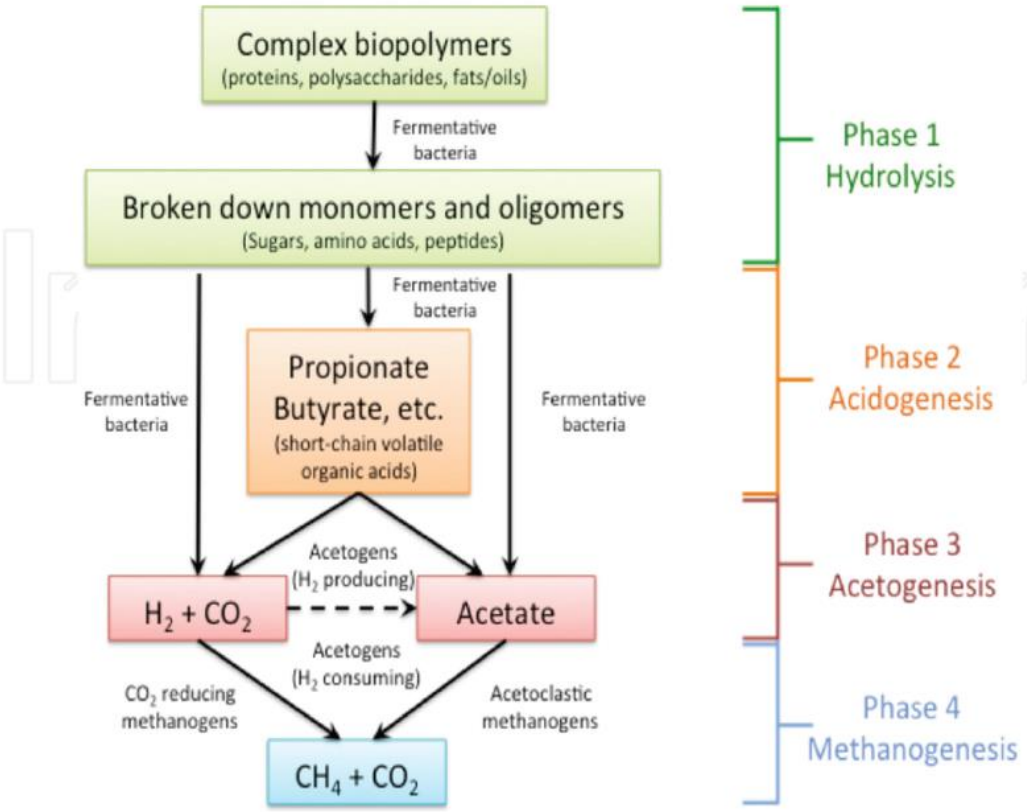


Figure 1.
Schematic representation of anaerobic digestion (source: https://www.e-education.psu.edu/egee439).

Volatile fatty acids (VFA)

The anaerobic microorganisms can be divided into:

1. Producers
    1. Enzyme producing microorganisms
    2. Fermenting microorganisms (producing VFA and H and CO2)
    3. Acetic acid producers

2. Consumers (Methanogens)
    1. Acidioclassic process
    2. Hydroenothrofic process

If acetic acids is not consumed completely, then VFA will accumulate and result in lowering of pH and pH<6 lead to dead of methanogens

Reactor technology - principles

Liquid feedstock: Two principles for reactors (< 10 -15 % d.m.):

1. Micro org. living on particles in substrate (CSTR) (~2 – 15 % d.m.)
2. Micro org. living permanent in the reactor (d.m. < 1 %)
   a) Granules (i.g. UASB, ABR)
   b) Biofilm

(Dry biogas fermentors)

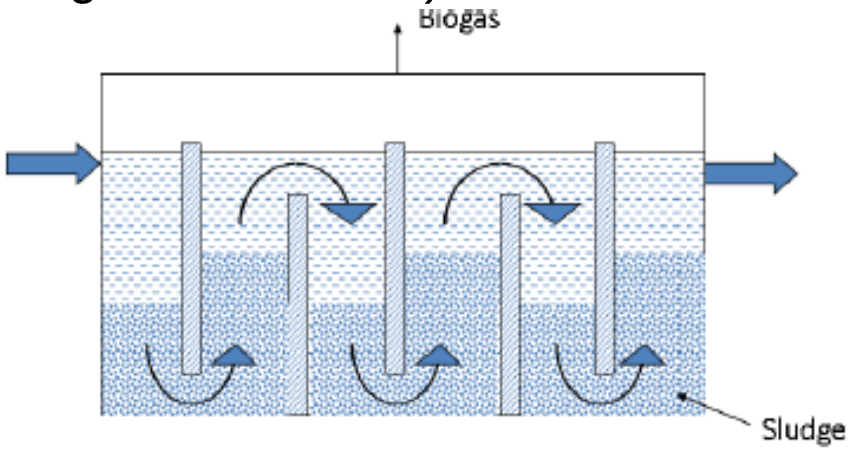
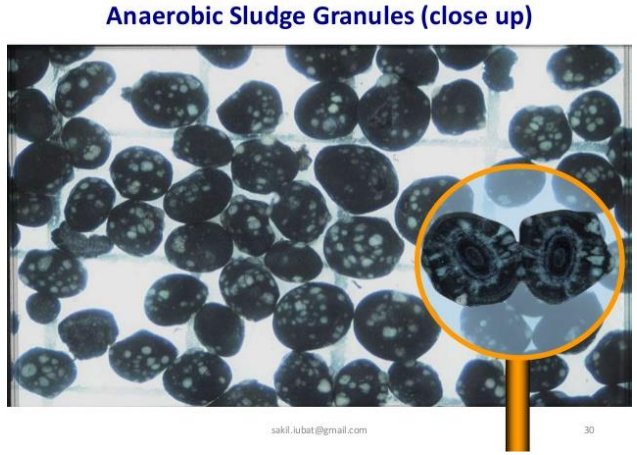
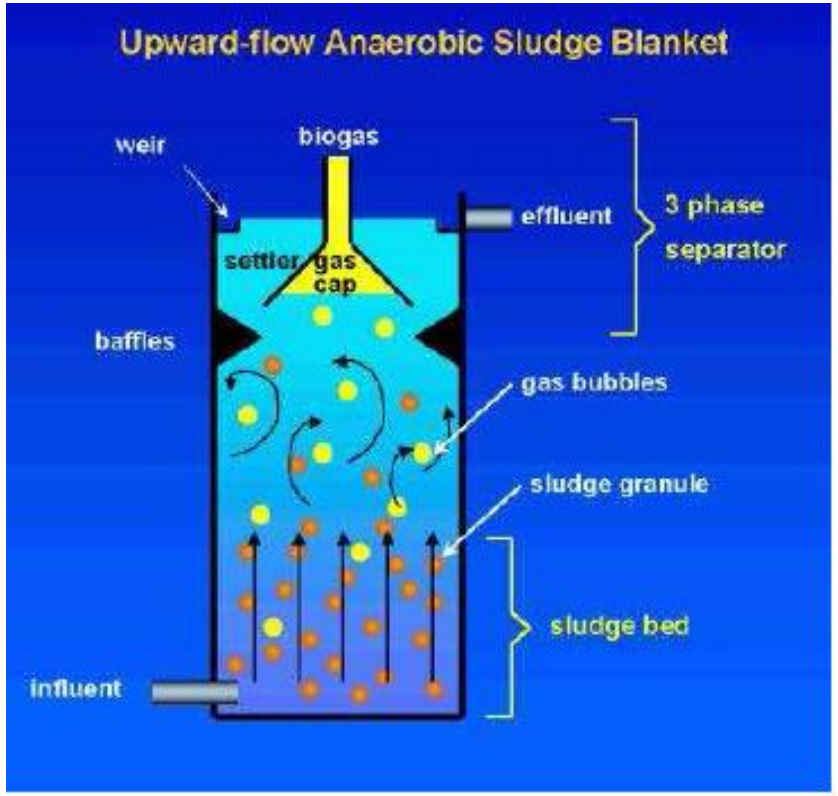


Figure 11: ABR design (Source: Paradigm Environmental Strategies, Bangalore, website: www.ecoparadigm.com)

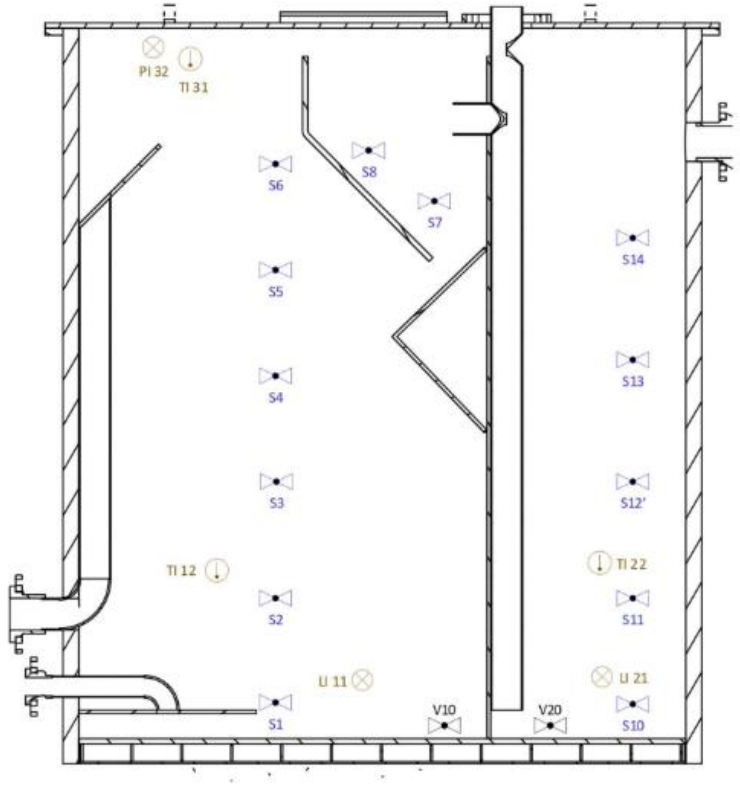




Example: reactor for black water

- Reactor design
  - Concept: UASB/ABR two chambers, recirculation in chamber 1.
  - Two chambers – totally 165 L
  - Feeding in pulses – 21 per day
  - Recirculation in pulses – 2 pulses between each feeding pulse
  - Temperature 28°C
  - Gas meter: Ritter TG1
  - Sampling points (S1 –S14)

- Reactor design



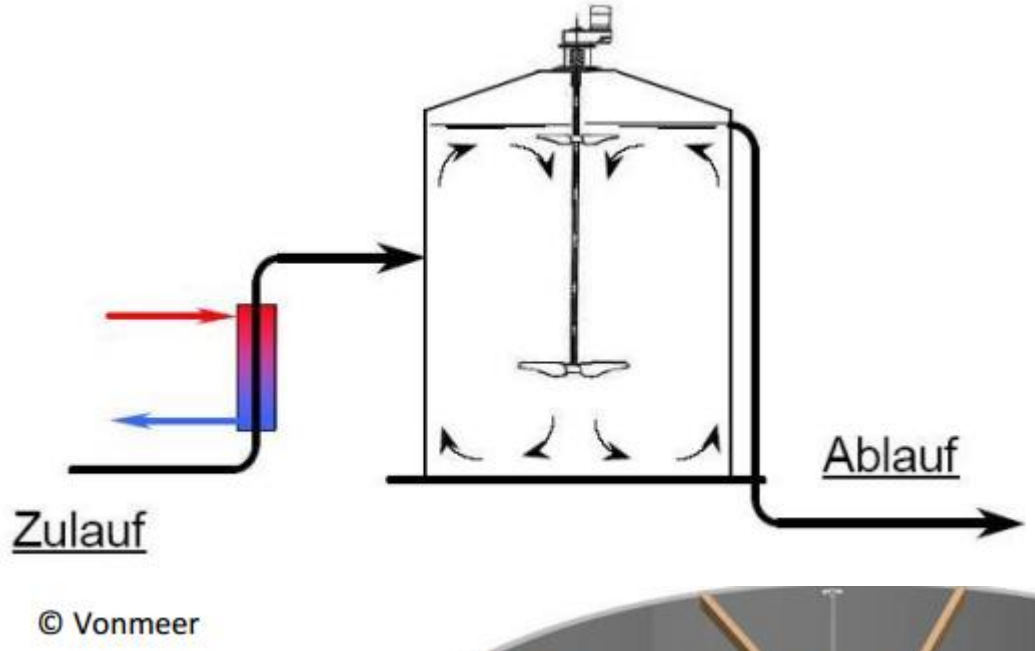
Results – performance of the reactor

Feed rate, biogas production, and methane content in the measuring period.

Period	Feed rate, L day^{-1}	Dry matter (dm), %	Volatile solids (VS), % of dm	Biogas yield, L day^{-1}	Methane content, %
55 days	31.03 +/- 3.37	0.64 +/- 0.13	70.3 +/- 2.74	97.6 +/- 5.4	69.3 +/- 4.3

- HRT: 5.3 days
- C/N ratio: 1.5/1-5.0/1
- FOS/TAC: 0.32 – 0.18
- pH: inlet 8.47 and outlet 7.67
- Results indicate specific biogas yield of 206 Nm^3/tonnes VS
- Recirculation pulses to avoid floating layer: 2 pulses between each feeding pulse of 3L/pulse

Reactor, CSTR



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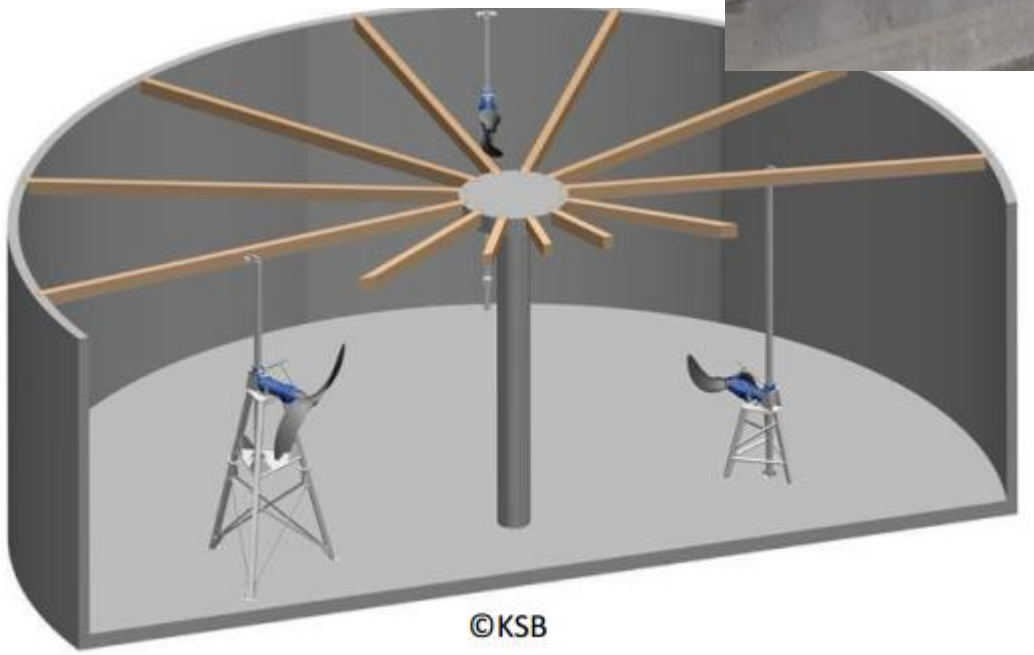

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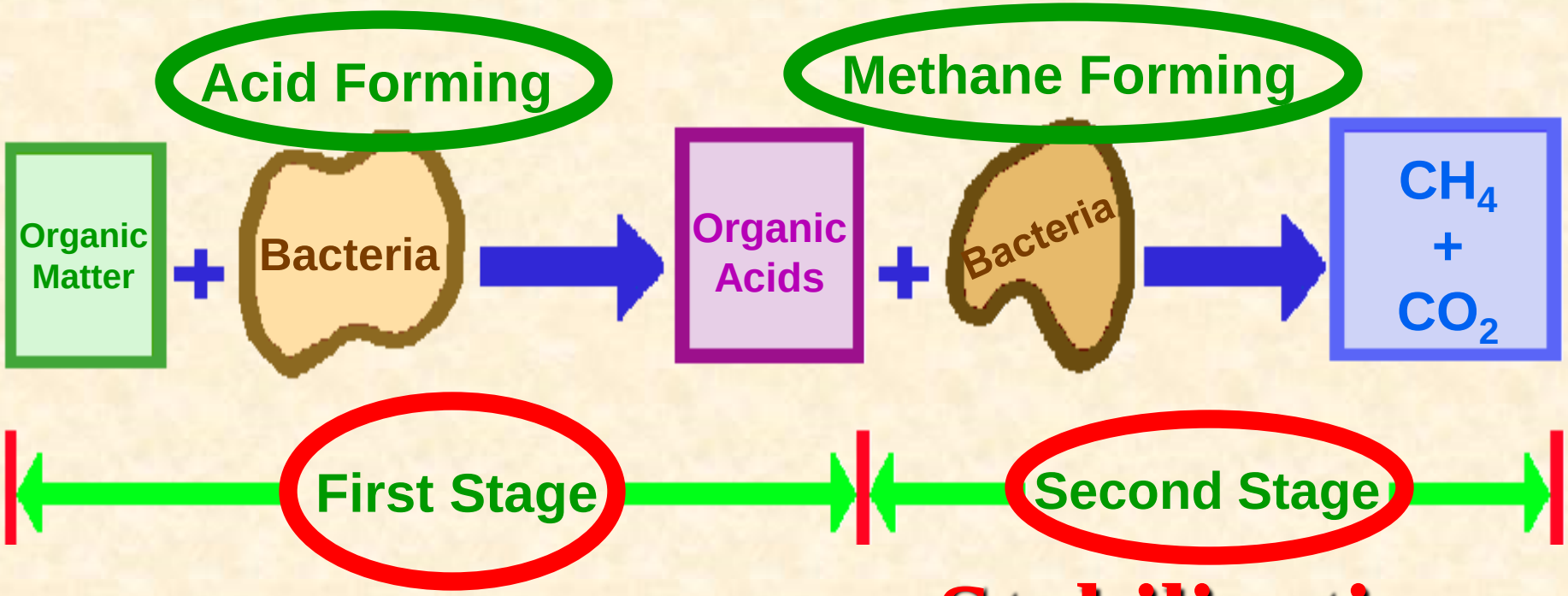
Anaerobic Digestion Process

Continuous Process

"TWO-STAGE" Process



Stabilization

Anaerobic Digestion Process

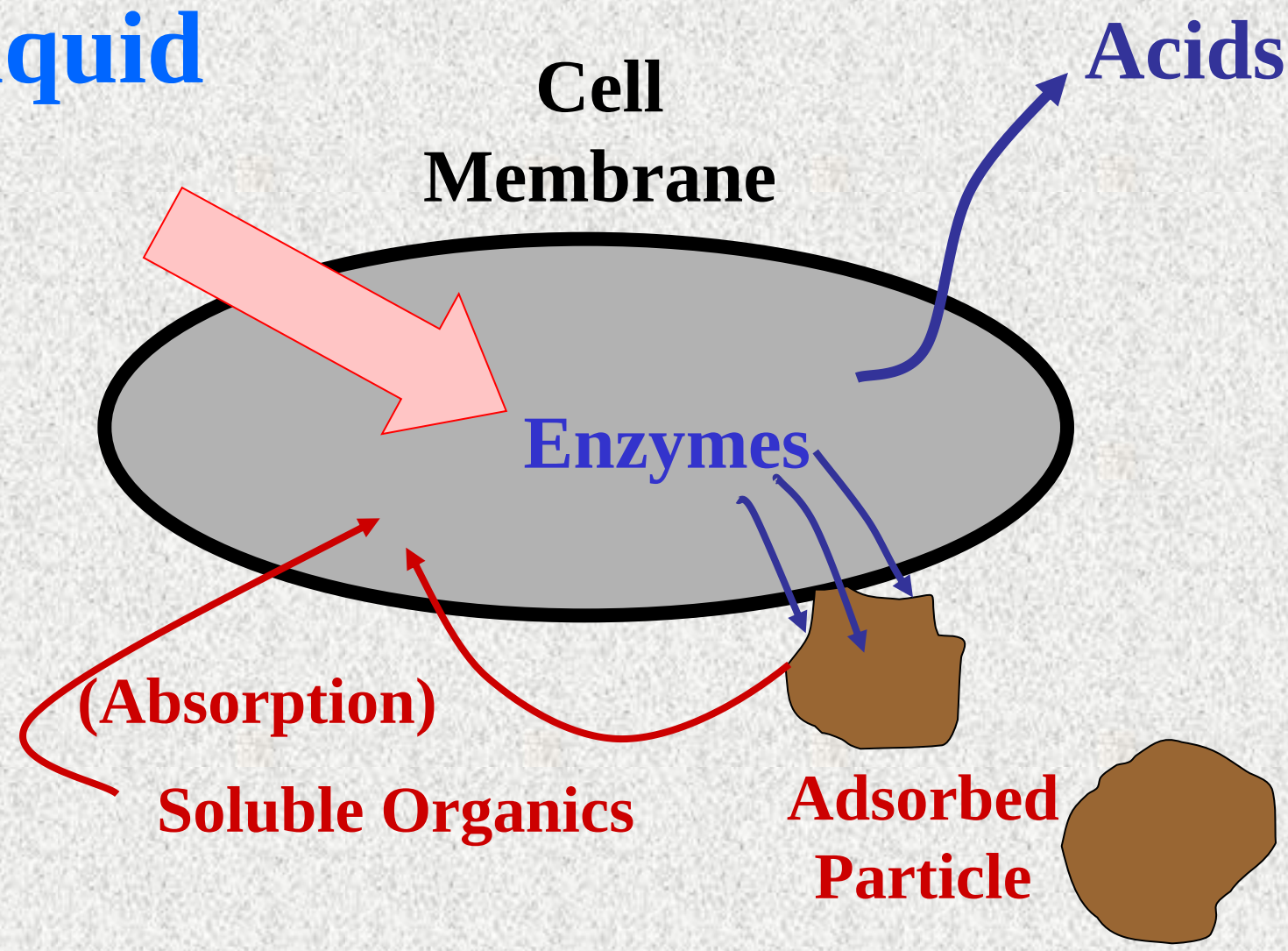
Type of Food

Organic

~~Inorganic~~

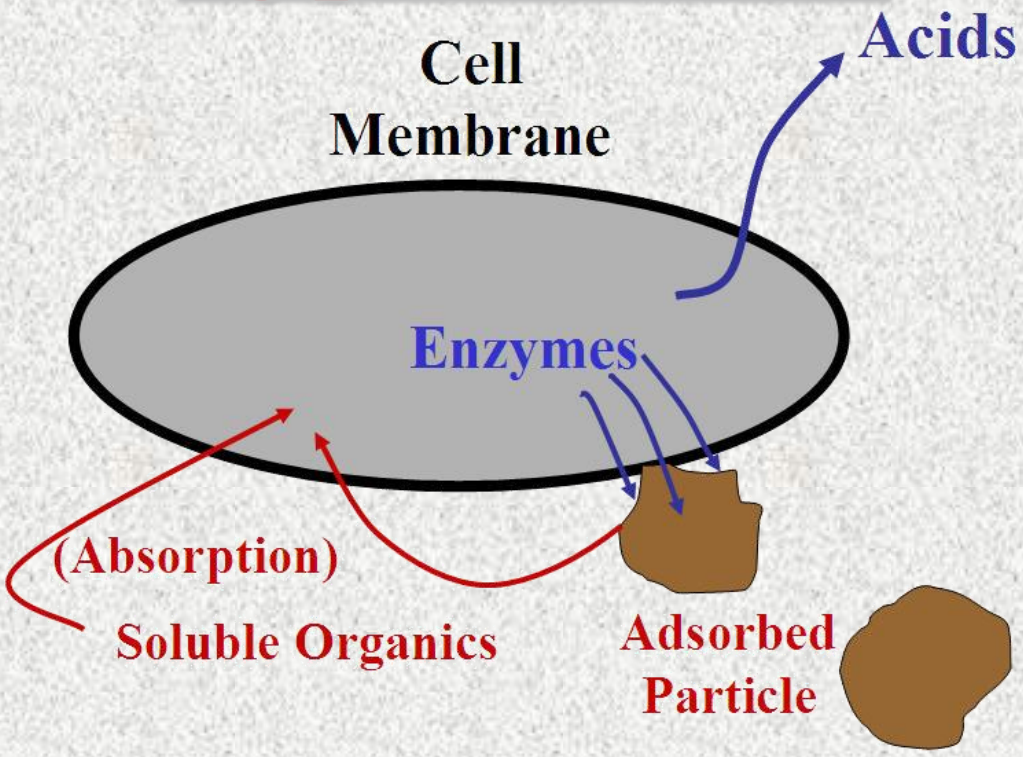
Soluble

Insoluble



Typical Acid Forming Bacteria

Type of Food



Not All Organic Material Broken Down

Poor Food - Not Readily Degradable

Inert Solids - Plastics, etc.

40 to 60 % of Organics are Reduced

Anaerobic Digestion Process

"TWO-STAGE" Process

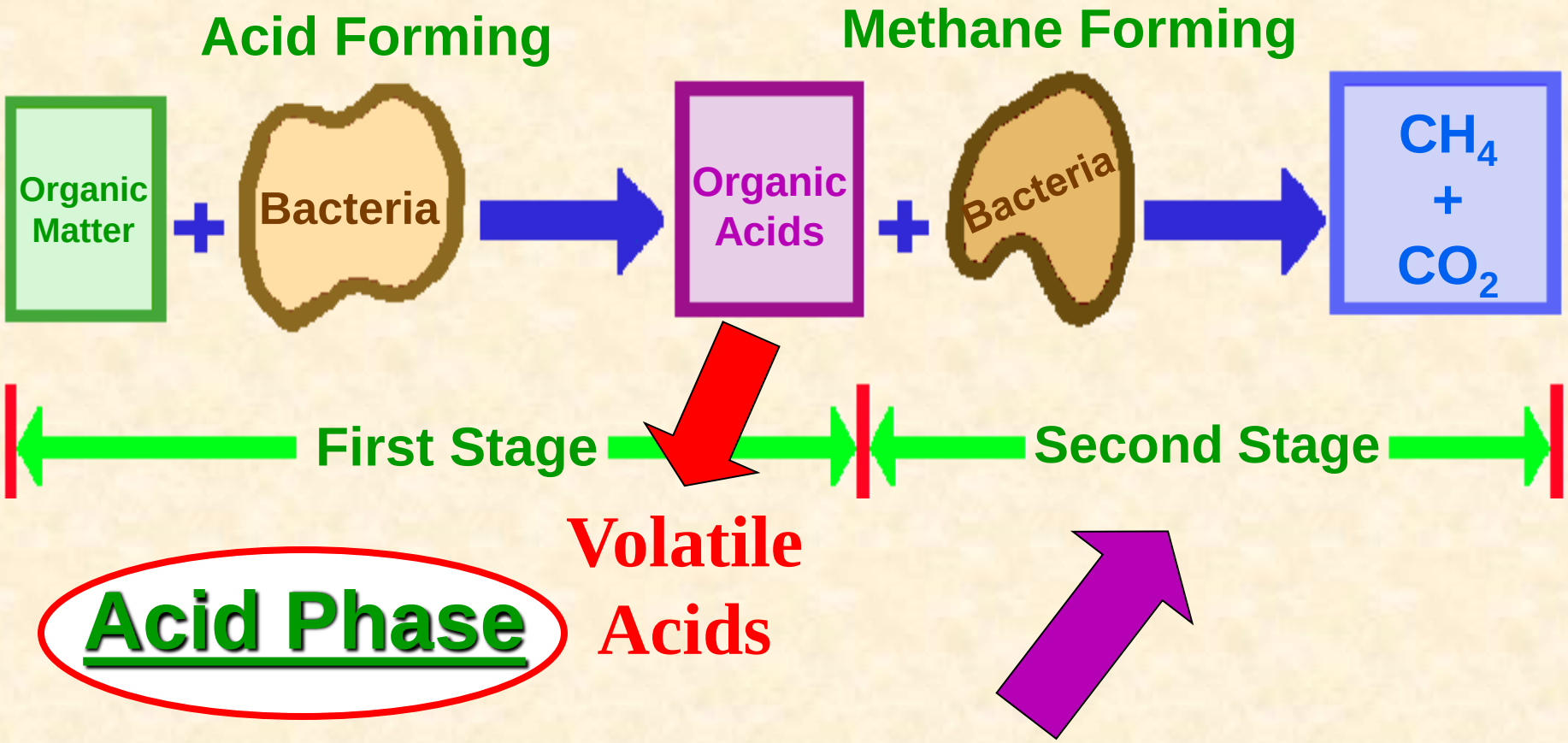
OR

"Two Phase" Process

Two Types of Bacteria
Each Relying On The Other

Must Be In Balance !

Anaerobic Digestion Process



Acids Used at Rate Produced

Anaerobic Digestion Process

Acids Used at Rate Produced

If Not Used - Drop in pH

Start-up

Upset

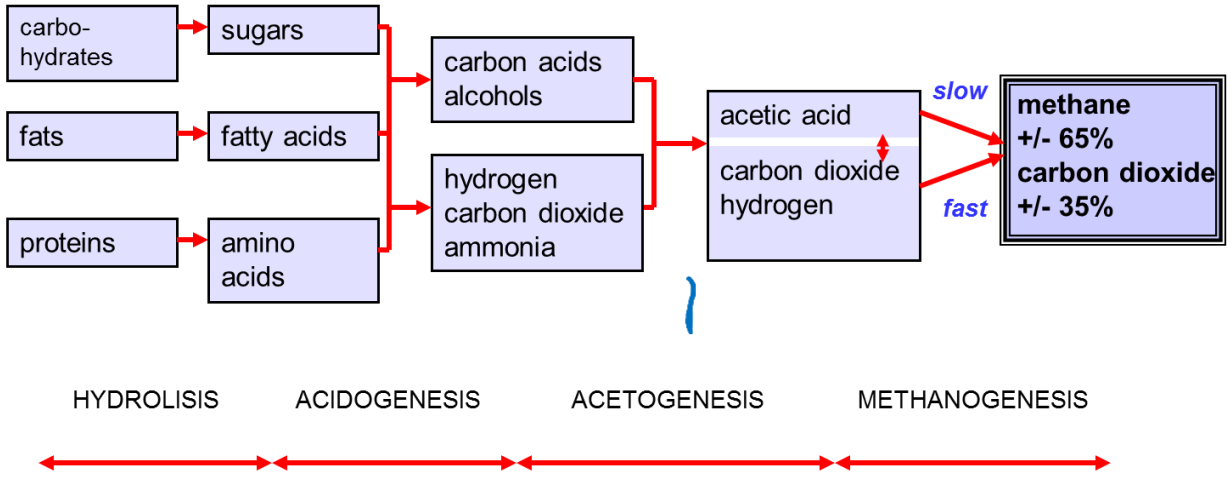
"Sour"

"Stuck"

Methane Formers Must Be Active

Balance of the process

- Producers and consumers
  - In a balanced process consumed substances must equalize produced substances
- Producers
  - Hydrolysis produce monomers
  - Acidogenesis consumes monomers and produce VFA, hydrogen and carbon dioxide. VFA are further degraded into acetic acid
- Consumers
  - Methanogenic archaea consume hydrogen, CO_2 and acetic acid



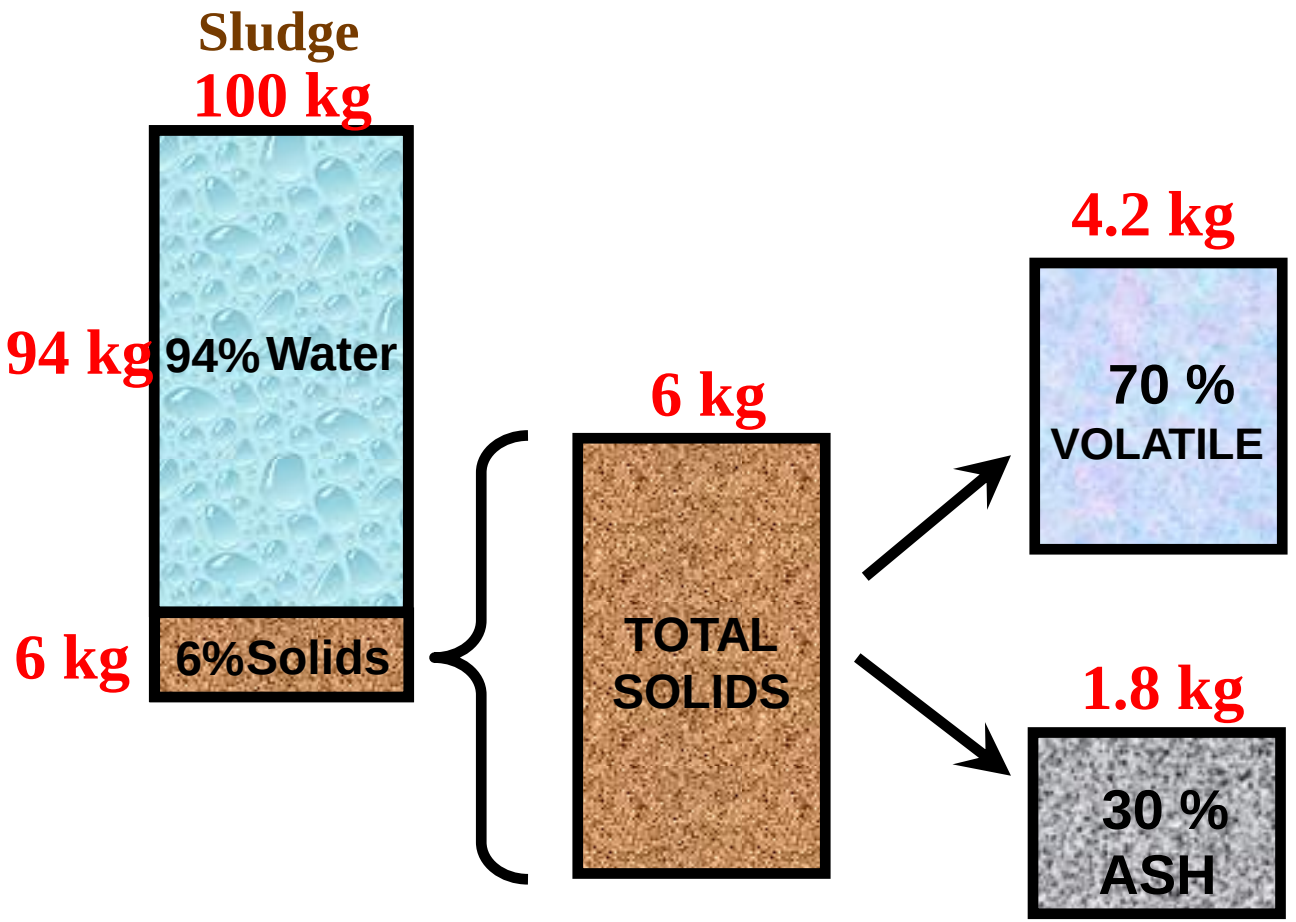
Anaerobic Digestion Process

Methane Formers:

- **Slow Growers**
- **Very Sensitive to Changes**
  - **Loading**
  - **pH**
  - **Temperature**

Digester Operation Depends On Maintaining Proper Environment for METHANE FORMERS

BALANCE !



SLUDGE SOLIDS DIAGRAM

Anaerobic Digestion Process

Products of Digestion

1. Gases

0.44 to 0.75 m3 per kg of volatile destroyed

Methane (CH_4)	65 to 70 %
Carbon Dioxide (CO_2)	30 to 35 %

6.5 – 7.0 kWh/m^3 biogas

Calculation of a plant

- **Useful terms:**
- Hydraulic retention time (HRT):

$$\mathrm{HRT} = \frac{V_R}{Q_s}$$

where Q_s is flow into the reactor/day and V_R is reactor volume.

- Organic loading rate (OLR):

$$\mathrm{OLR} = \frac{Q_s \times \mathrm{VS_{in}} \times \mathrm{TS_{in}}}{V_R}$$

where Q_s is flow into the reactor/day, $\mathrm{VS_{in}}$ is VS content in incoming substrate, $\mathrm{TS_{in}}$ is TS content in incoming substrate and V_R is reactor volume.

- Degradation:

$$\mathrm{VS_{red}} = \frac{Q_s \times \mathrm{VS_{in}} - Q_r \times \mathrm{VS_r}}{Q_s \times \mathrm{VS_{in}}}$$

where Q_s is flow into the reactor, Q_r is flow out of the reactor and $\mathrm{VS_r}$ is VS content in effluent.