ENV-405 Session 2 Wastewater treatment Lecture 7 Dec 16

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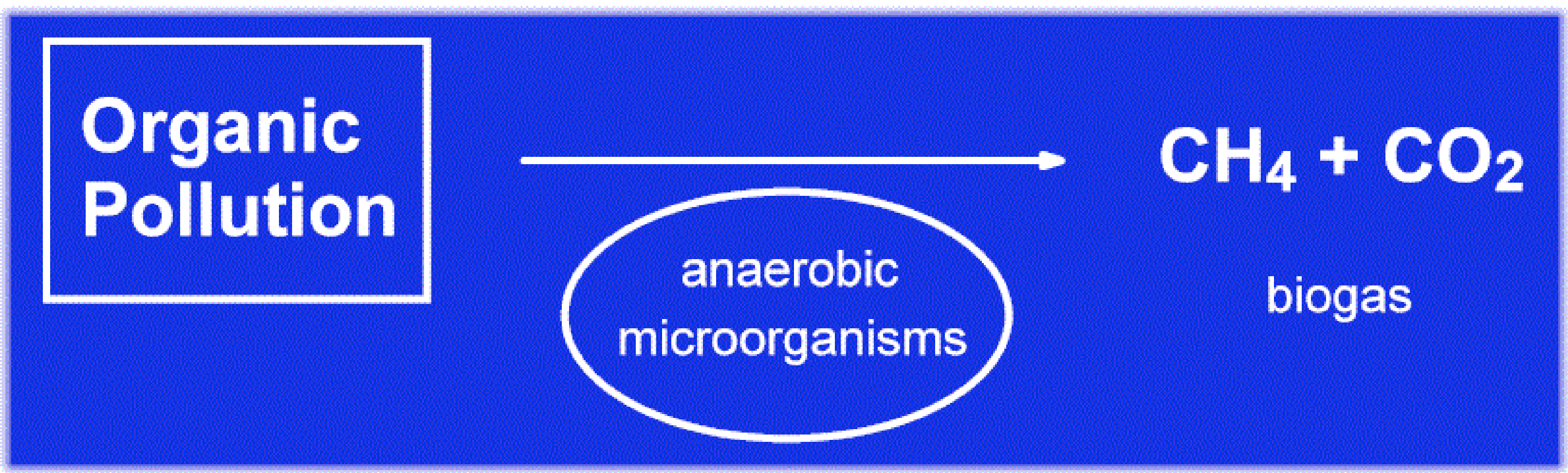
Slides acknowledgment: Christof Holiger, Shilva Shretha

Today’s content

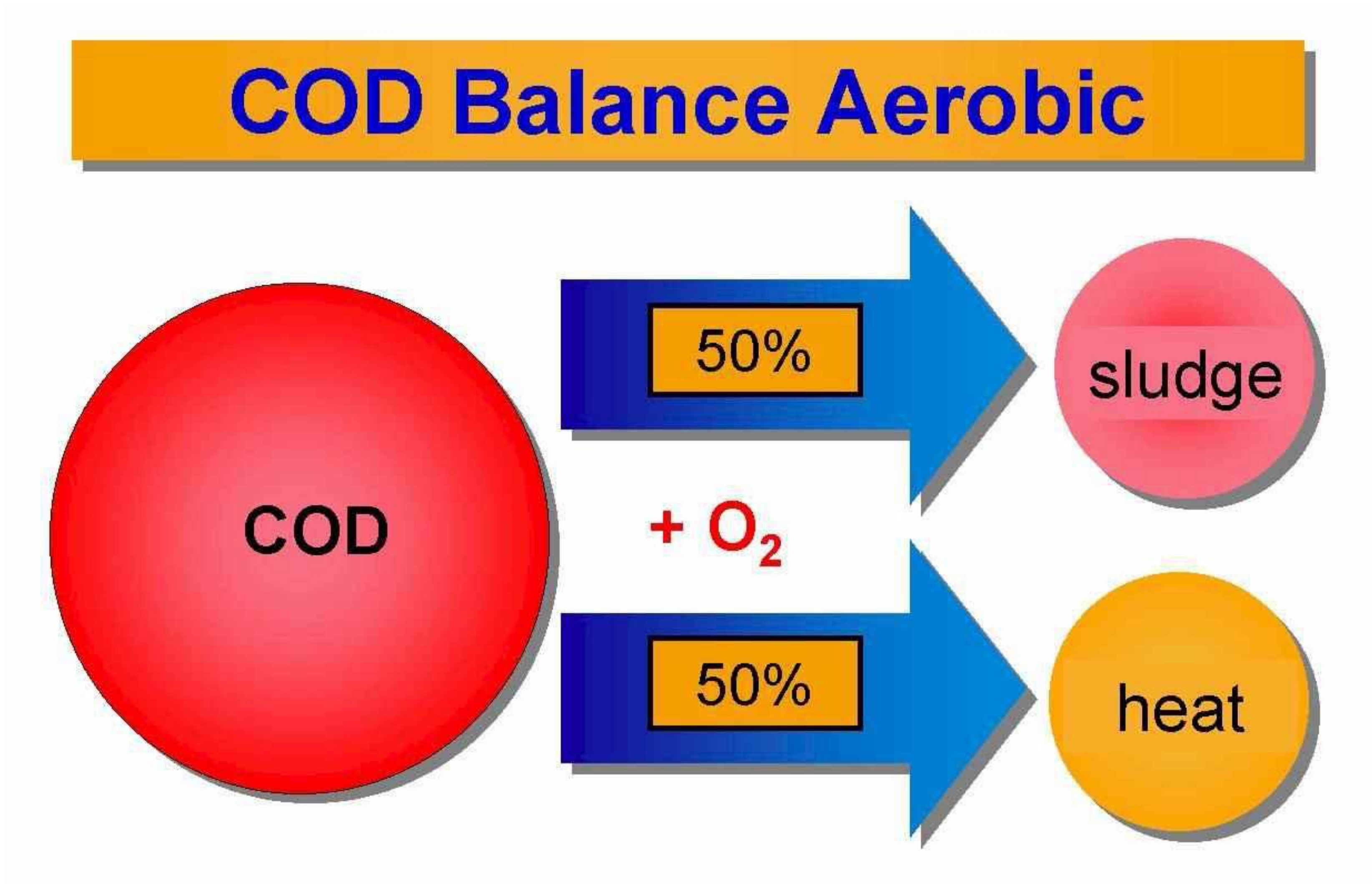
- Anaerobic digestion theory
- AD reactor design

Anaerobic Digestion: Theory

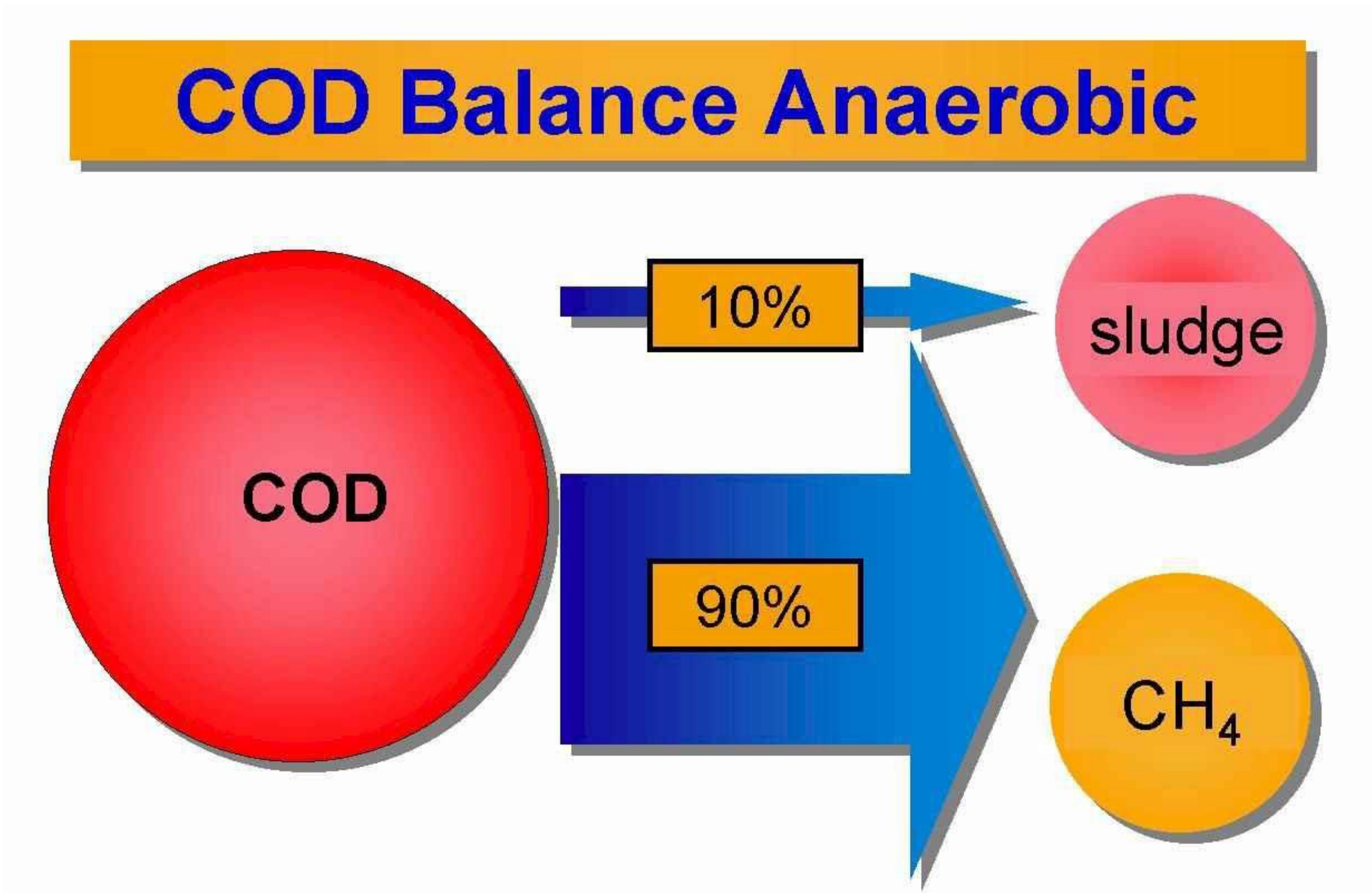
- The biochemical reactions in the anaerobic digestion process are multistep
- The product from an upstream reaction performed by one group of microorganisms becomes the reactant for a downstream reaction performed by a different group of microorganisms.
  - Some of the products can be inhibitory.



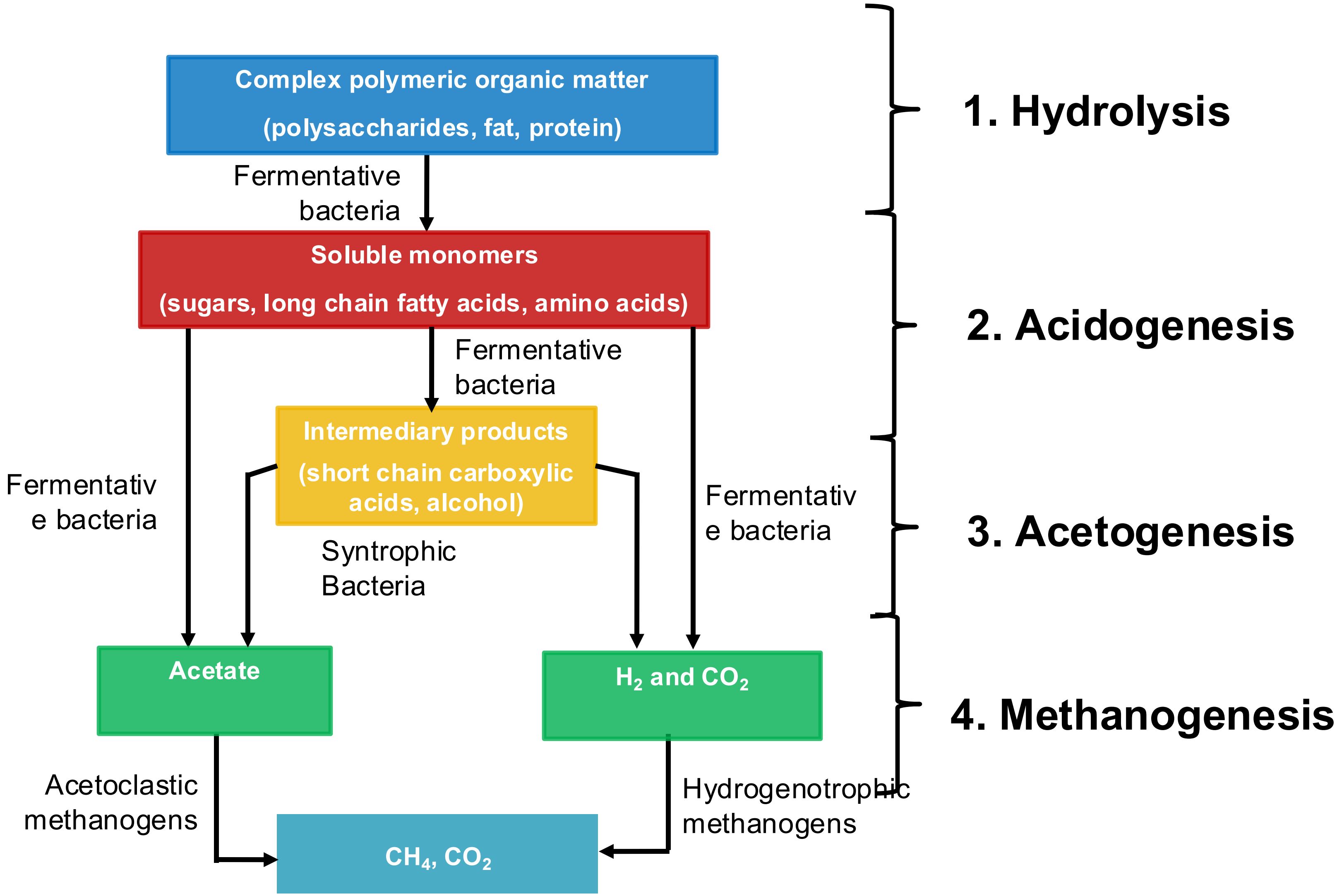
COD Balance Aerobic Biodegradation



COD Balance Anaerobic Biodegradation

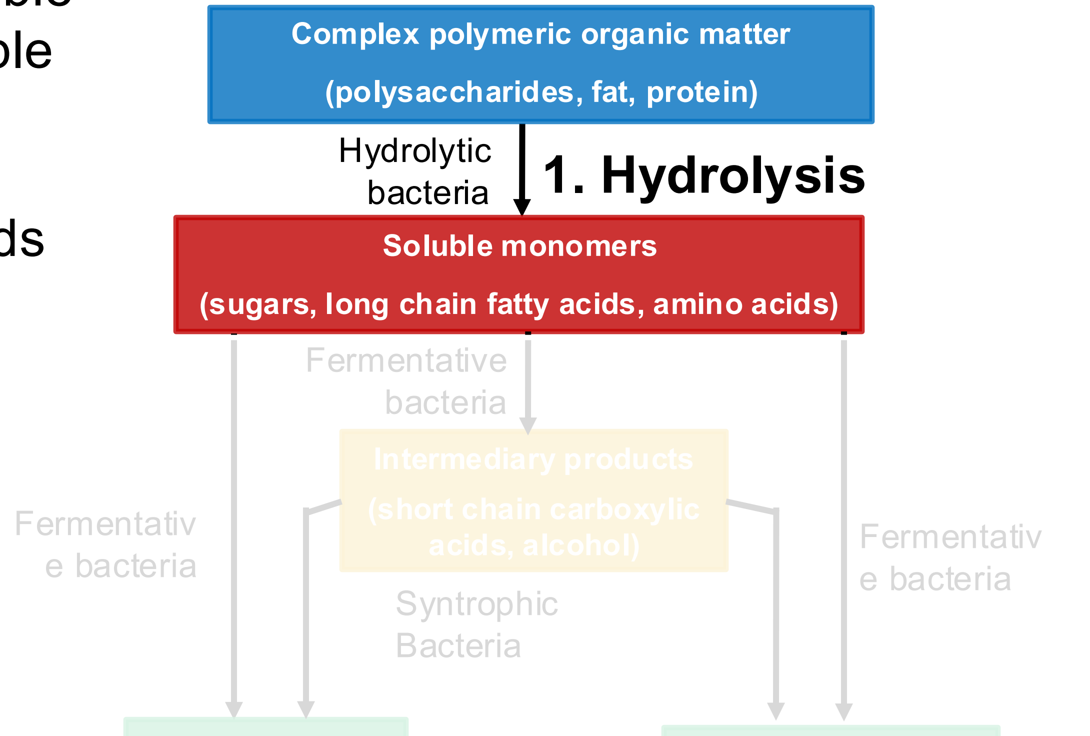


Anaerobic Digestion



Hydrolysis

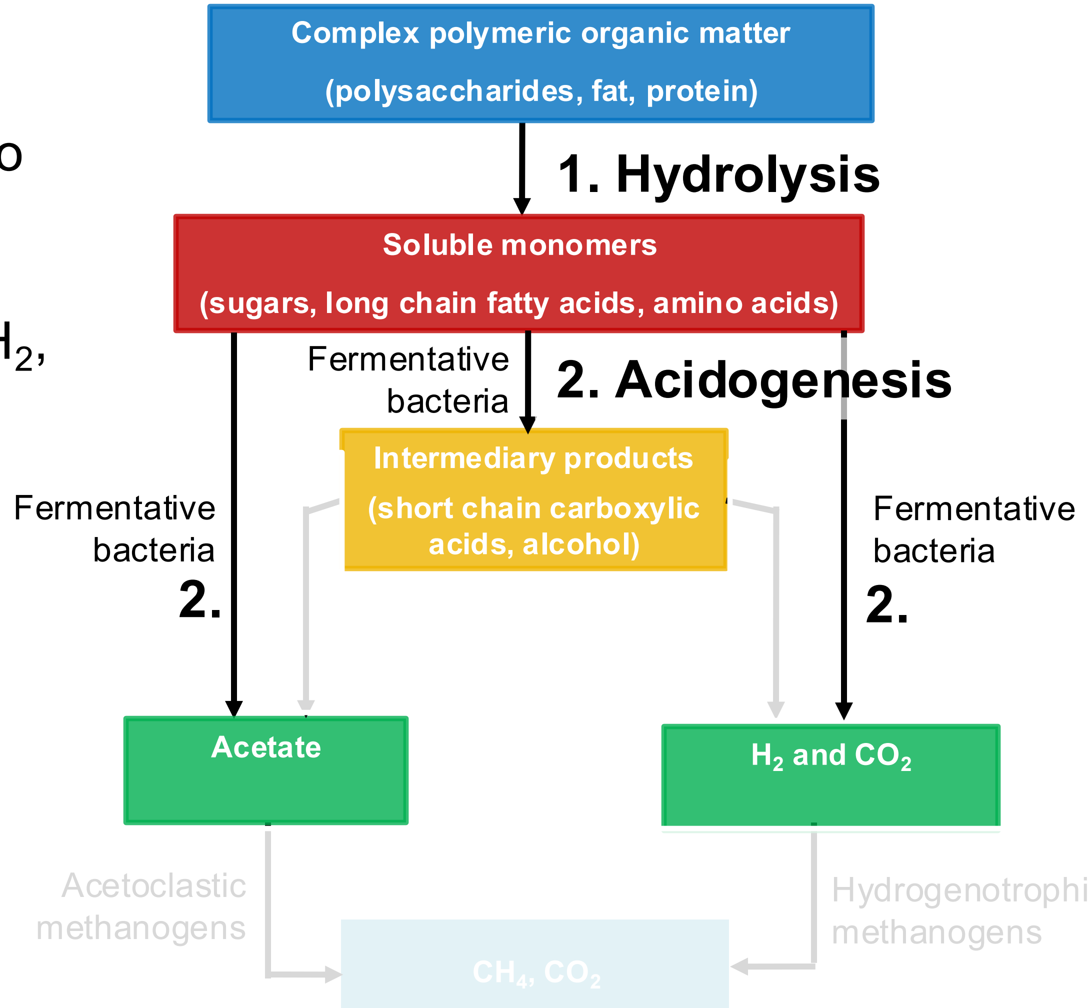
- Hydrolytic bacteria decompose insoluble particulate organics into simpler soluble forms
  - carbohydrates into simple sugars, proteins into amino acids, and lipids into mostly long-chain fatty acids.
- Employ extracellular enzymes
- Rate-limiting for solid waste streams
- Extracellular hydrolytic enzymes:



Substrate to be degraded	Enzymes needed
Cellulose	Endoglucanases, Exoglucanases, β-glucosidases
Hemicellulose	Xylans degradation: endo-1,4- β –xylanase, β -xylosidase, α-glucuronidase, -L-arabinofuranosidase, and acetylxylan esterase Glucomannan degradation: β -mannanase, and β -mannosidase
Lignin	Manganese peroxidase,lignin peroxidase, laccase

Acidogenesis

- Hydrolyzed products are converted to short chain fatty acids (acetate, butyrate, propionate, valerate) and minor amounts of lactate, alcohols, H_2, and CO_2.
- Metabolized by acidogenic or fermentative bacteria
- ~50% of organic carbon to acetate, ~20% to CO_2, and remaining is converted to non-acetate SCCAs

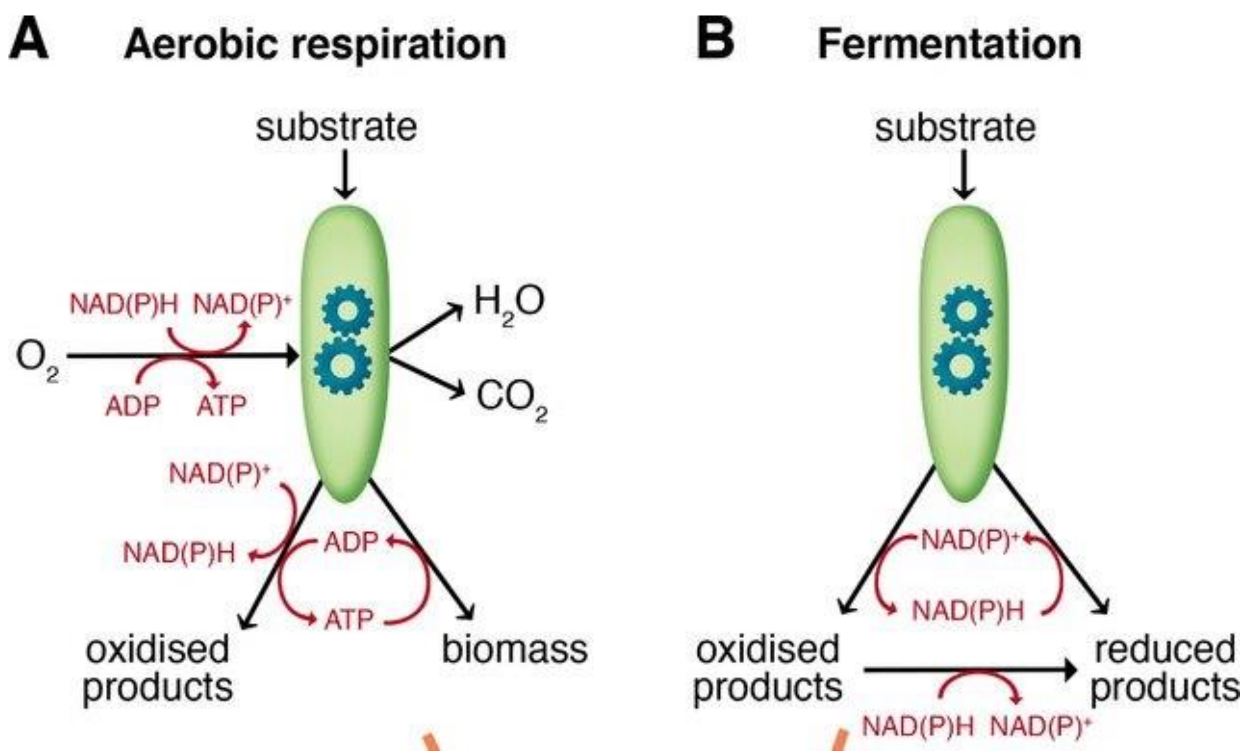


SCCAs: Short chain carboxylic acids (C1-C5)

Sometimes, acidogenesis is also referred to fermentation process

During this process, organic compounds (e.g., sugar) serve as electron donors.

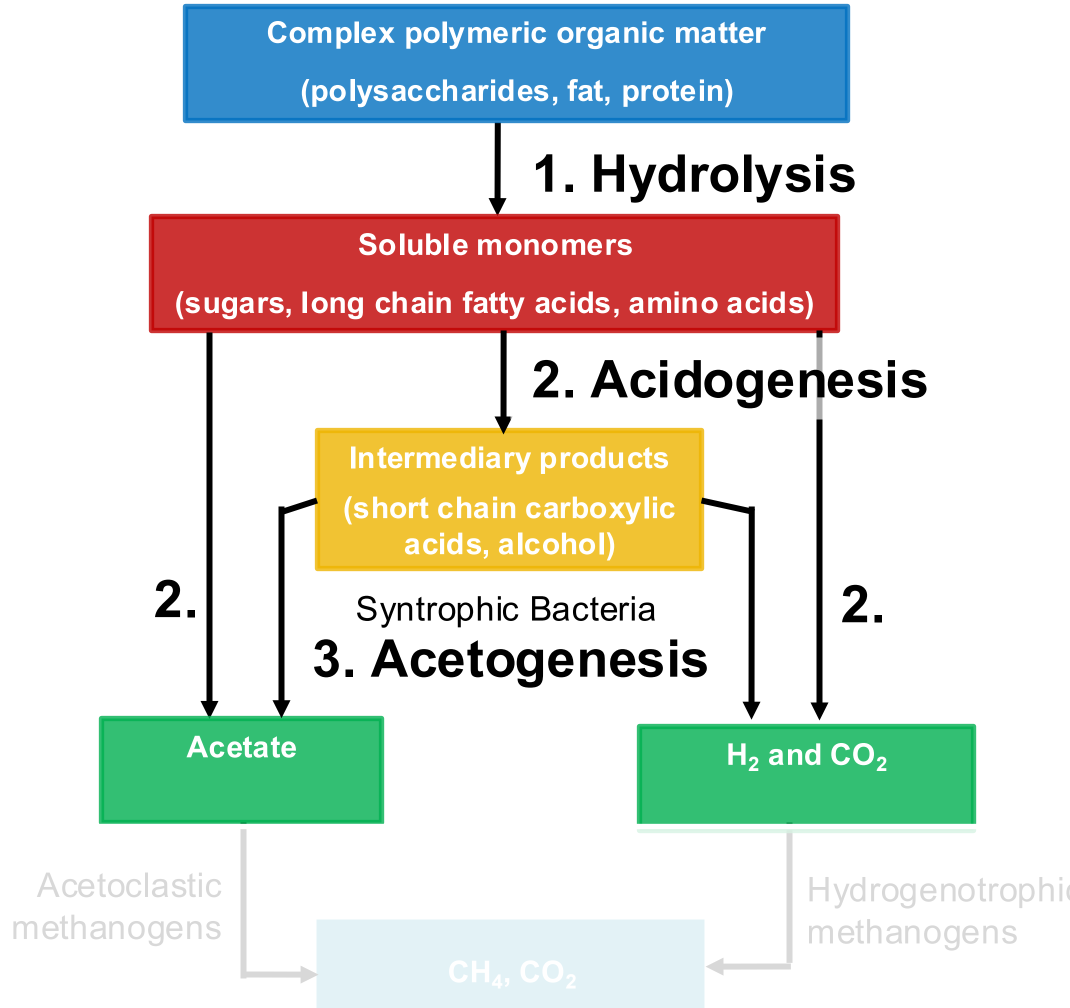
Internal organic products/Intermediates serve as electron acceptors.



Acetogenesis

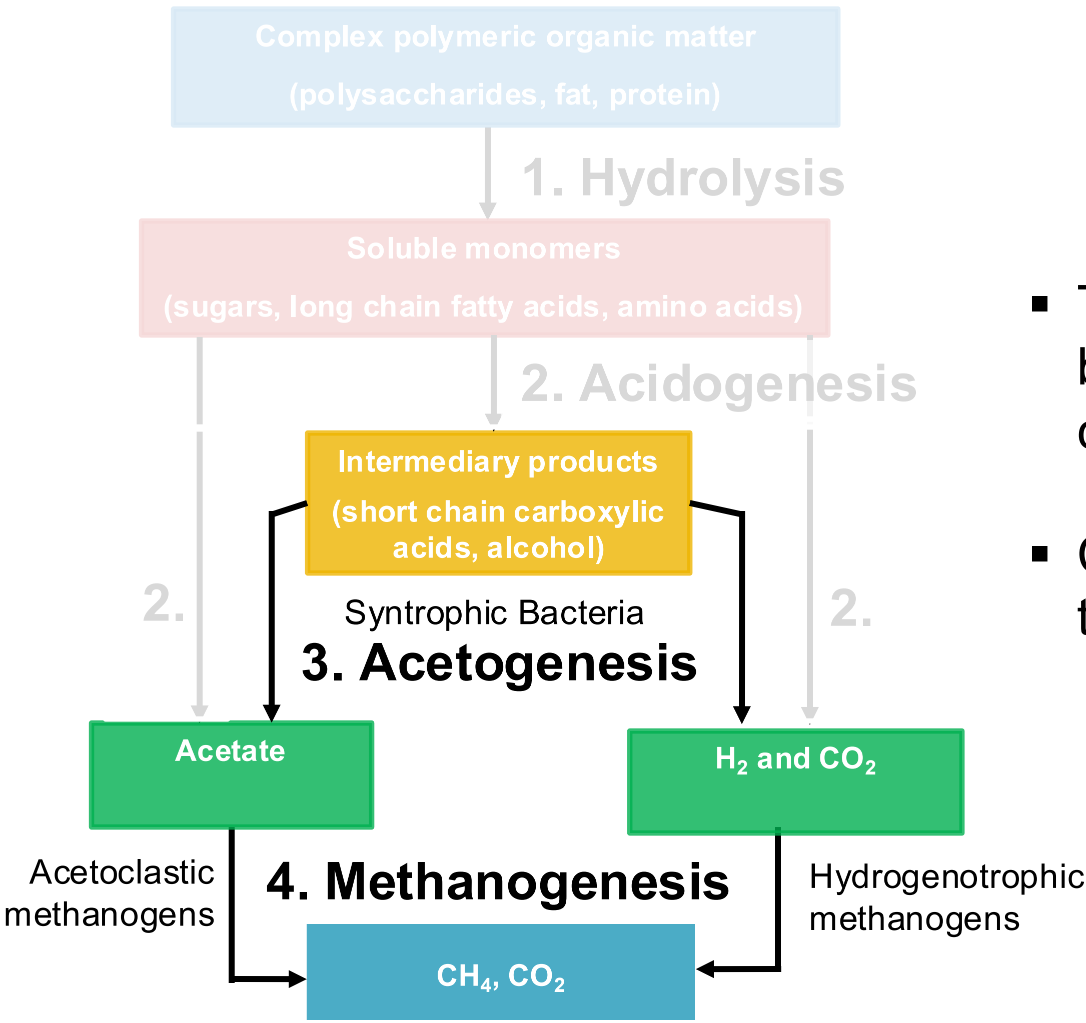
- Non-acetate SCCAs+ alcohol are converted into acetate, CO_2, and H_2

- H_2 producing acetogens or Syntrophic fatty acid oxidizing bacteria



SCCAs: Short chain carboxylic acids (C1-C5)

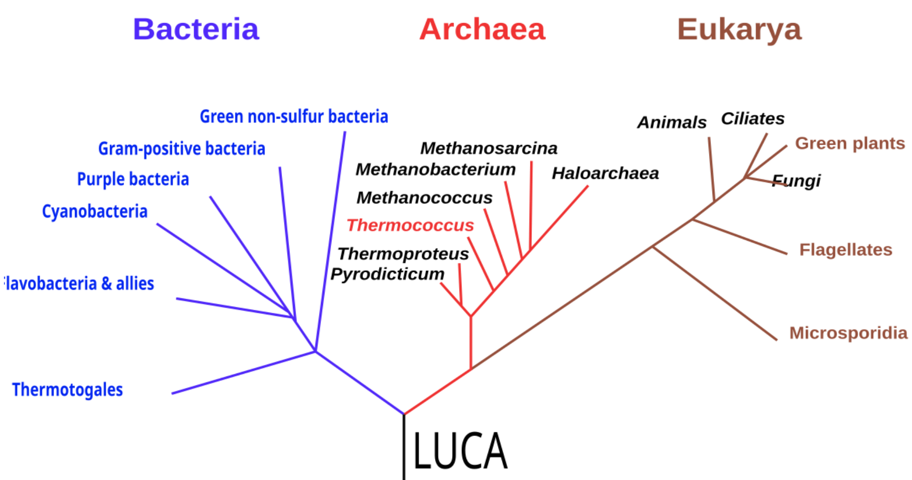
Syntrophic reactions during anaerobic digestion

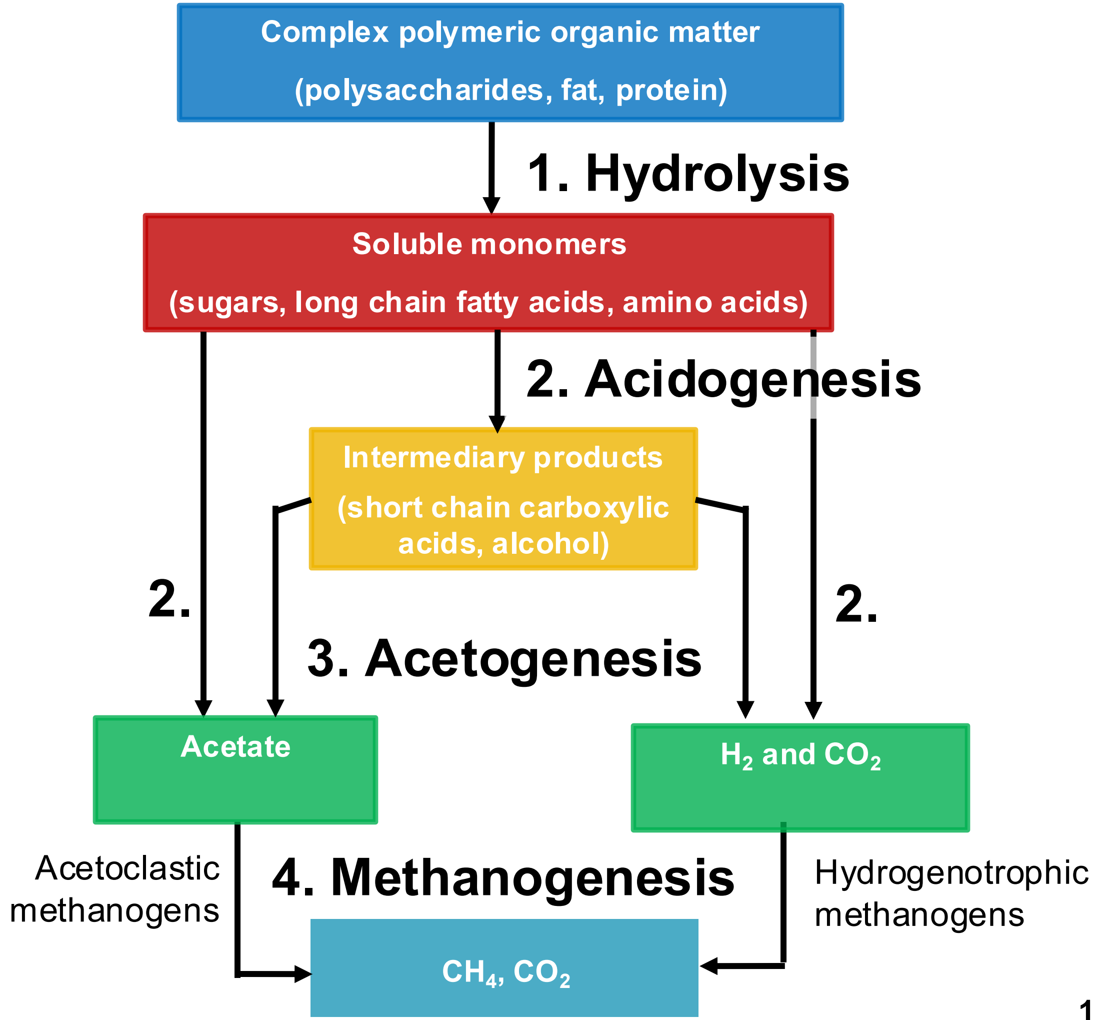


- There exists a syntrophic association between H_2 producing acetogens and H_2 consuming hydrogenotrophs
- Commonly known as interspecies H_2 transfer

Methanogenesis

- Final metabolic stage of anaerobic digestion
- Catalyzed by strictly anaerobic ***Archaea*** called methanogens
- Present in sediments, animal guts, sewage sludge digesters





Methanogenic Reactions

acetoclastic methanogenesis

$$CH_3COOH \longrightarrow CH_4 + CO_2$$

acetate → methane + carbon dioxide

autotrophic methanogenesis

$$CO_2 + H_2 \longrightarrow CH_4$$

carbon dioxide + hydrogen → methane

Kinetic Parameters Anaerobes

	Doubling Time	Cell Yield	Cell Activity	Ks
	days	g VSS g-1 COD	g COD g-1 VSS d-1	mM
Activated Sludge (sugar)				
Aerobic Bacteria	0.030	0.40	57.8	0.25
Acidification (sugar)				
Fermentative Bacteria	0.125	0.14	39.6	ND
Acetogenesis (fatty acids)				
Acetogenic Bacteria	3.5	0.03	6.6	0.4
Methanogenesis				
Autotrophic (H2)	0.5	0.07	19.6	0.004
Acetoclastic (acetate)				
Methanosarcina	1.5	0.04	11.6	5.0
Methanosaeta	**7.0**	0.02	5.0	0.3

Uses: Anaerobic Processes

1. Sludge digestion
2. High-strength wastewater
3. SCCA (also called VFA) production to support EBPR (enhanced biological phosphorus removal)
4. Help to remove xenobiotics via specific anaerobic pathways
5. Land application of biosolids

Anaerobic digestion is a process used to "stabilize" wastewater sludge and convert it into biosolids, which are then prepared for land application.

What does “stabilize” mean?

Reduction of volatile solids.
Reduce odor.
Long retention time at mesophilic conditions also reduces pathogens.
Improved dewaterability (destruction of the organic cell structure).

Advantages of anaerobic processes

Low sludge production
No oxygen requirement
Produces methane (Biogas)
Low nutrient requirement

Disadvantages of anaerobic processes

Long SRT → large footprint
Slow startup, slow recovery after upsets
Sensitive to operating conditions – pH, temp
Insufficient alkalinity for diluted or carbohydrate rich waste streams
Sulfide and odor generation if sulfate is present in feed
Cannot remove nutrients

What to do with the rest of the”nutrients” after AD treatment?

Switzerland has a progressive and strict environmental policy, and it officially **banned the direct application of sewage sludge (including digested sludge/biosolids) to agricultural land starting in 2003, with the full ban implemented by 2006.**

The decision was driven by the **Precautionary Principle**, which states that if there is a risk of severe or irreversible harm to the environment or public health, a lack of full scientific certainty should not be used as a reason for postponing cost-effective measures to prevent environmental degradation.
While digested sludge is rich in valuable **Nitrogen (N)** and **Phosphorus (P)**, the ban was put in place due to the contaminants that enter the wastewater stream and become concentrated in the sludge.

Accumulation of heavy metals, micropollutants (PFAS, microplastics), risk of pathogens.

By spreading sludge directly onto fields, authorities lose control over where the accumulated contaminants end up. Incineration, the mandated alternative, provides a defined, measurable output (ash) that allows for better control and recovery of specific resources.

Anaerobic Digester: Configuration variety

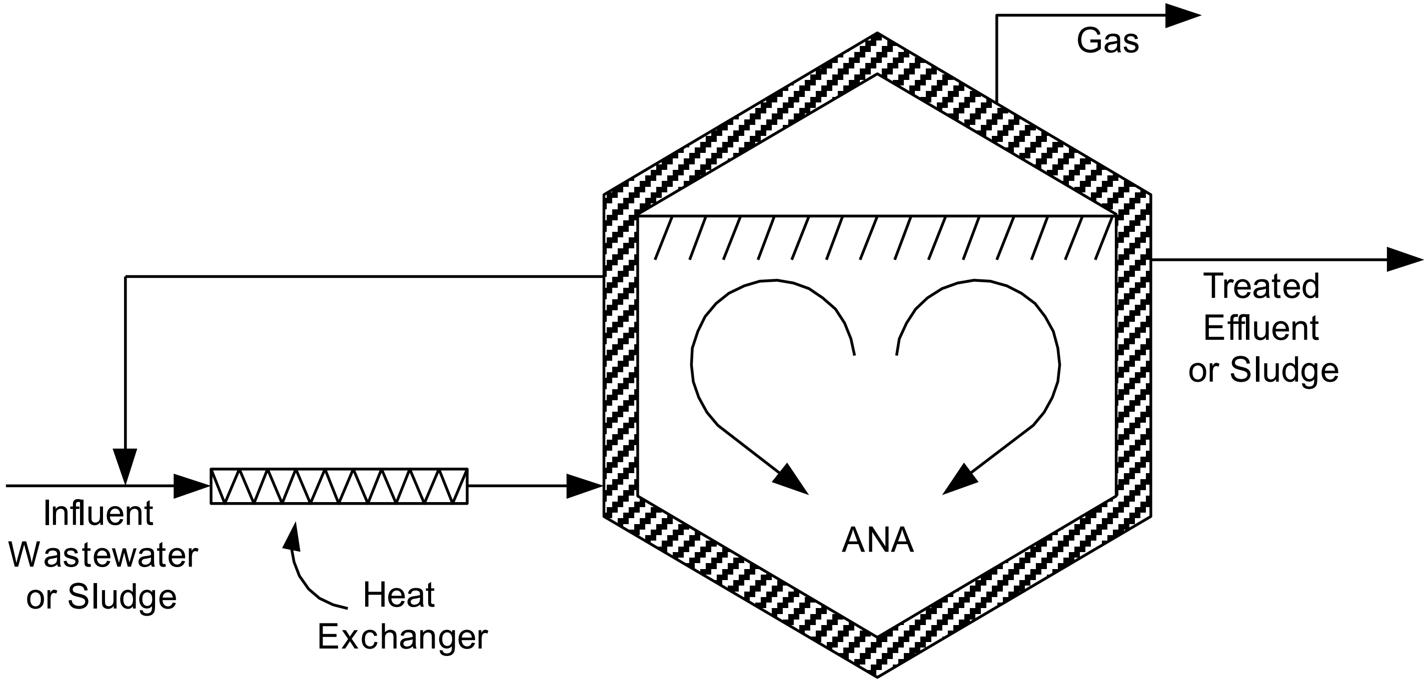


Figure 14.1 Anaerobic bioreactor.

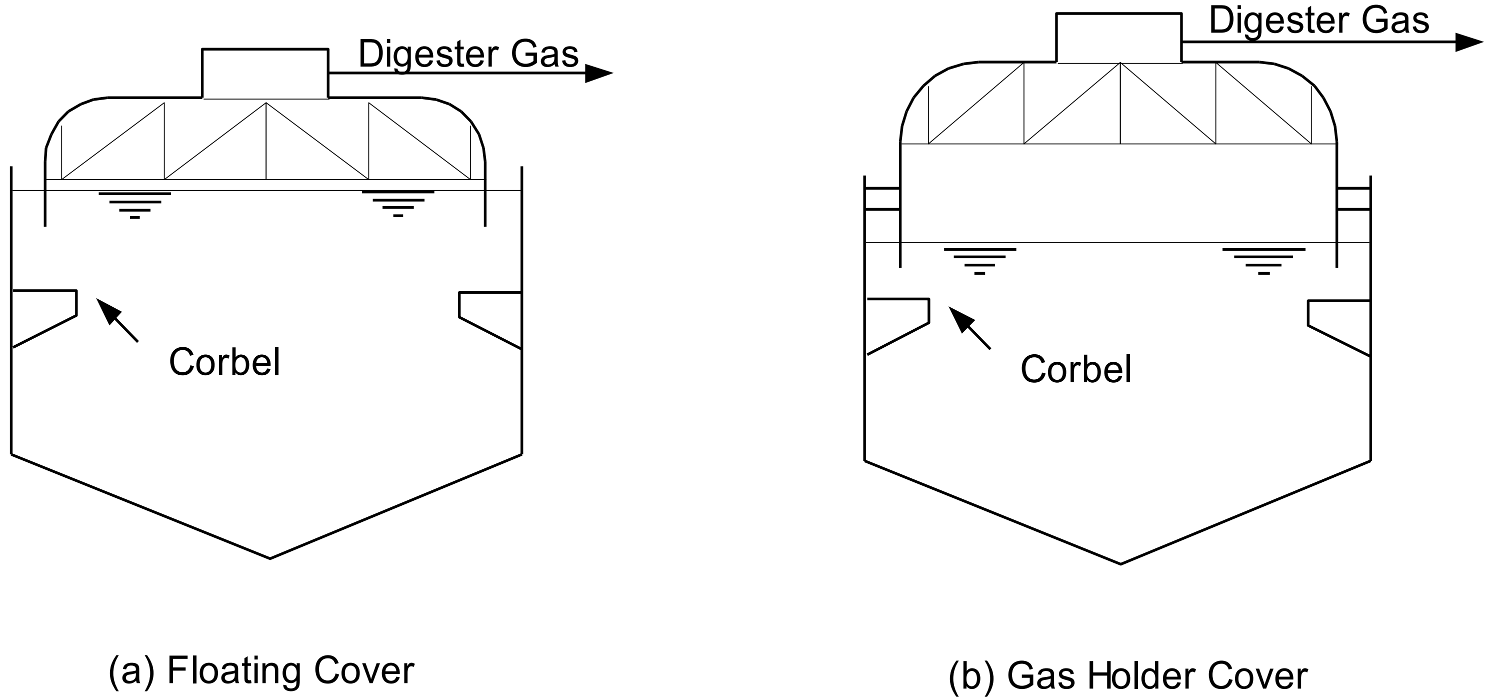


Figure 14.2 Gas storage covers for anaerobic digesters.

Anaerobic Digester: Configuration

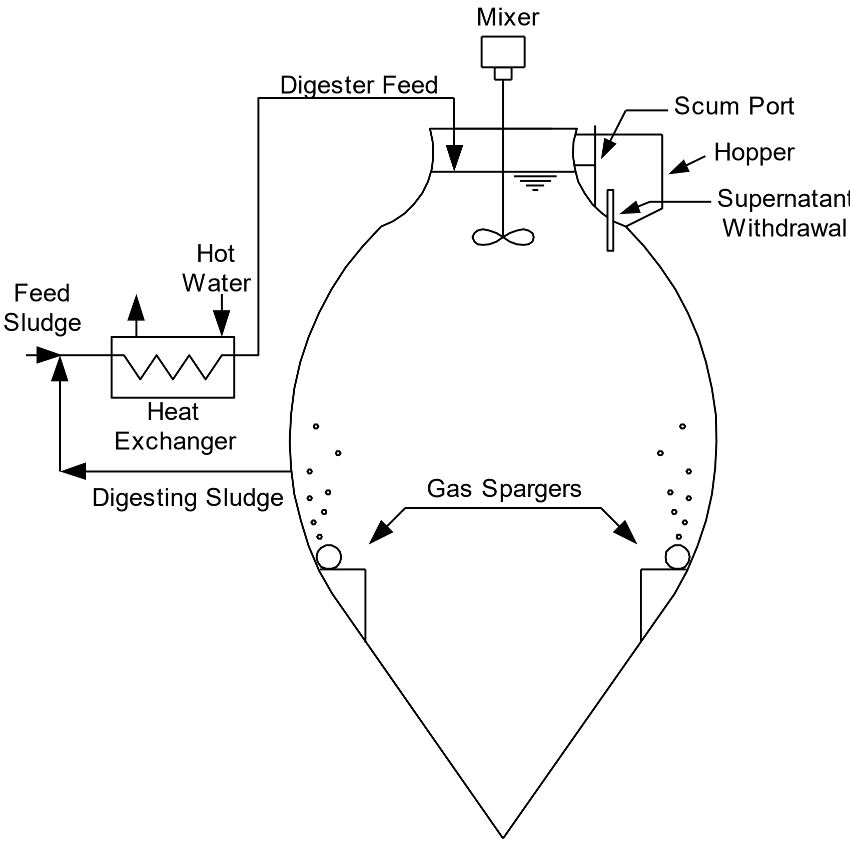
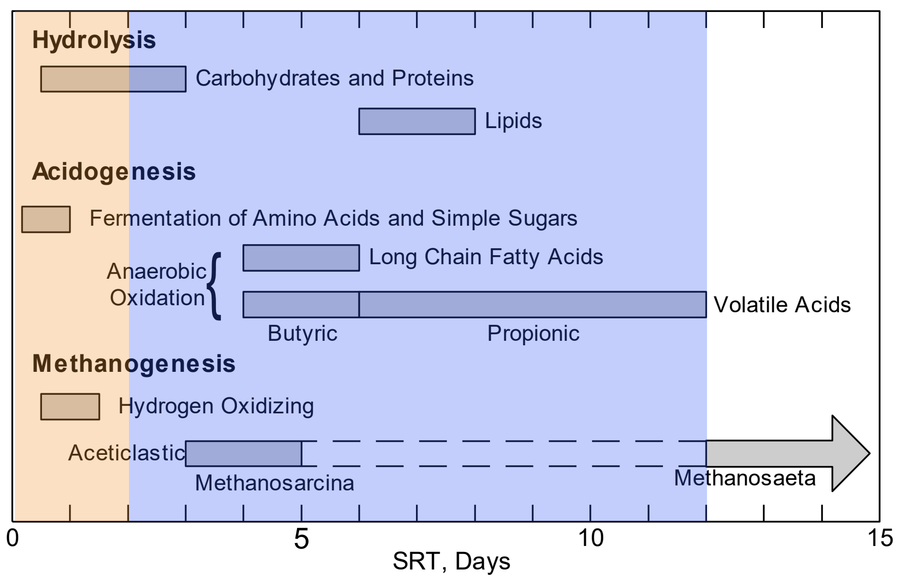


Figure 14.3 Egg shaped anaerobic digester.

Two-phase anaerobic digester

Separate growth condition for fermentation and methanogenesis
Acid phase (1-2 day SRT) + gas phase (10 day SRT)
High efficiency
Better flexibility



- The acid-formers work quickly, producing Volatile Fatty Acids (VFAs) as intermediates.
- If the feedstock is loaded too quickly (i.e., a high Organic Loading Rate OLR), the acid-formers produce VFAs faster than the slow-growing methane-formers can consume them.
- Since the methane-formers are highly pH sensitive, their activity is inhibited or stops completely.
- This is called **"souring"** the digester, which can lead to system failure and is the primary reason for instability in single-stage AD.

How would a separate reactor help with the whole process?

- First stage microorganisms are much less pH sensitive than methanogens → increase OLR, increase acid production
- CO_2 produced during methanogenesis and ammonia left behind act as buffers in the 2^{nd} reactor.
- Over-dilution of acids from the first phase. (e.g., 2 volume of 1st reactor with 4-6 volumes of 2nd reactor)

Operation schemes:

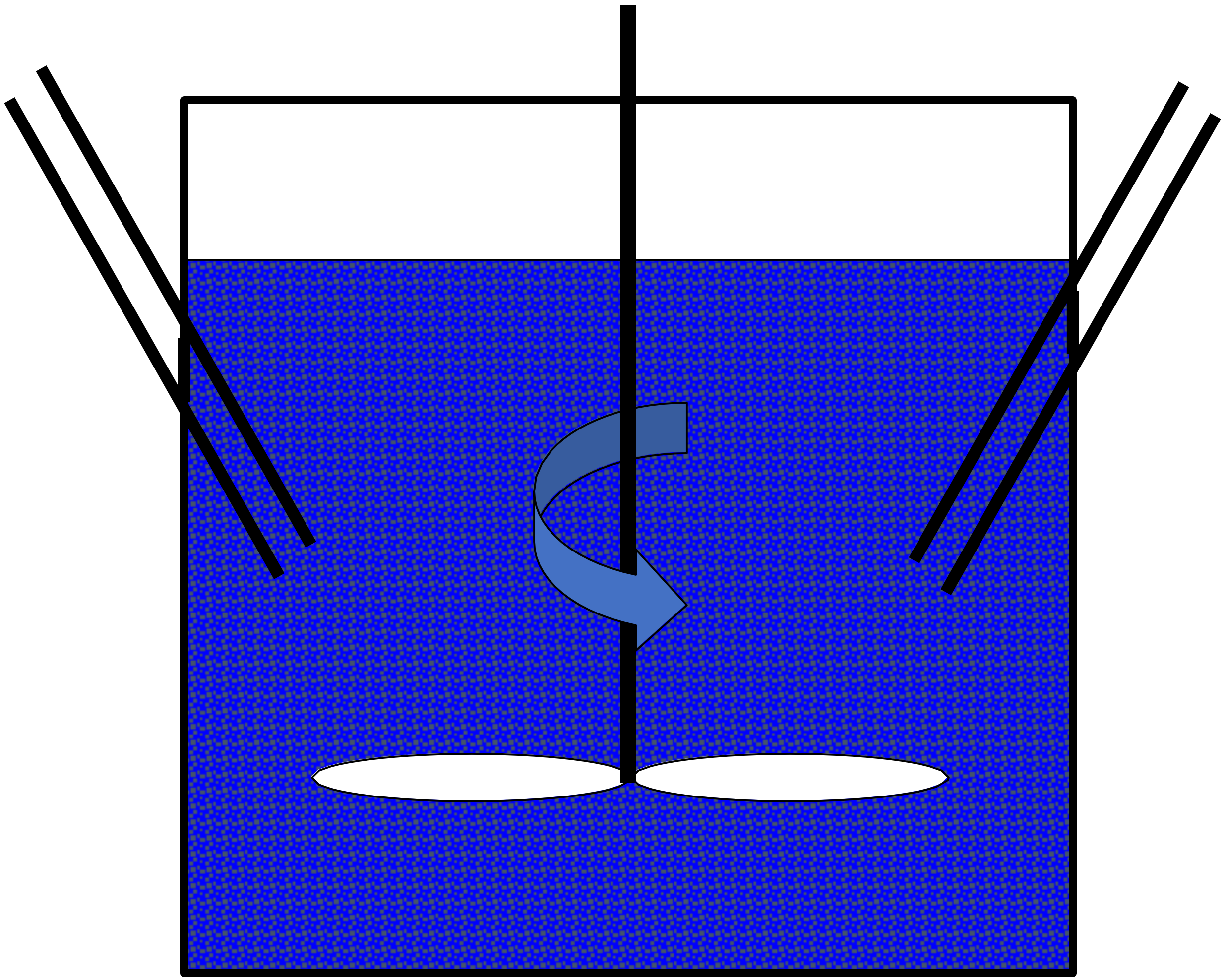
Feature	Low-Rate Anaerobic Process (CSTR, PRF, Batch)	High-Rate Anaerobic Process (UASB, EGSB, AF, AnMBR)
Primary Use	To stabilize and reduce the volume of **sewage sludge.**	To treat **flowing wastewater** (especially high-strength industrial effluent).
Sludge Type	Flocculent sludge (conventional, low-density aggregates).	Granular sludge (dense, fast-settling pellets).
Hydraulic Retention Time (HRT)	Long (15 to 45 days, often equal to SRT).	Short (a few hours to a day).
Mixing	Often intermittent or only partial (allowing layers to form).	Complete and continuous (to maintain biomass contact).
Result	Stabilized, reduced-volume biosolids + Biogas.	Treated water + Biogas + High-value seed sludge.

CSTR

Dilution Rate (1/HRT) Time < Max. growth Rate

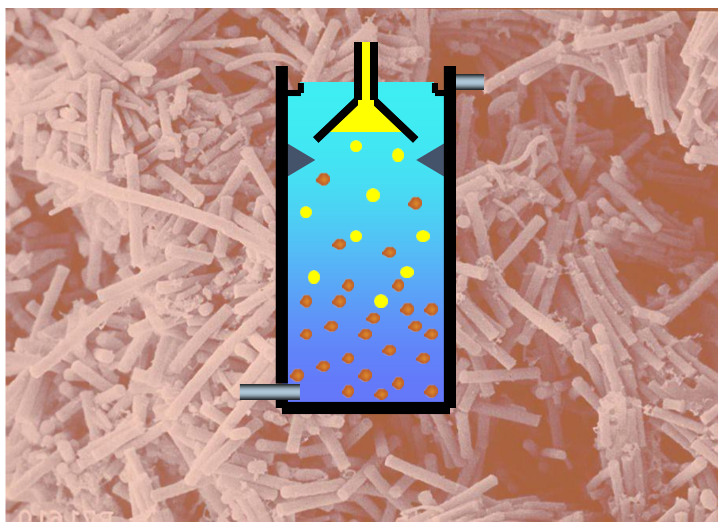
Methanosaete (t_d =7 d), growth rate = $\ln(2)/t_d$ = 0.1 d^{-1}

so minimum HRT = 10 days



High-Rate Anaerobic Wastewater Treatment

- Smaller space requirement
- Wastewater strengths to 20,000 mg/L COD (industrial sectors like food beverage, pulp and paper treatment)
- SRT>HRT
- Generally preferred for wastewaters containing low to no suspended solids



Anaerobic membrane bioreactor (AnMBR)

Ultrafiltration membrane – perfect separation of SRT and HRT

- Long solids retention at high flow rate

→ small footprint, high efficiency

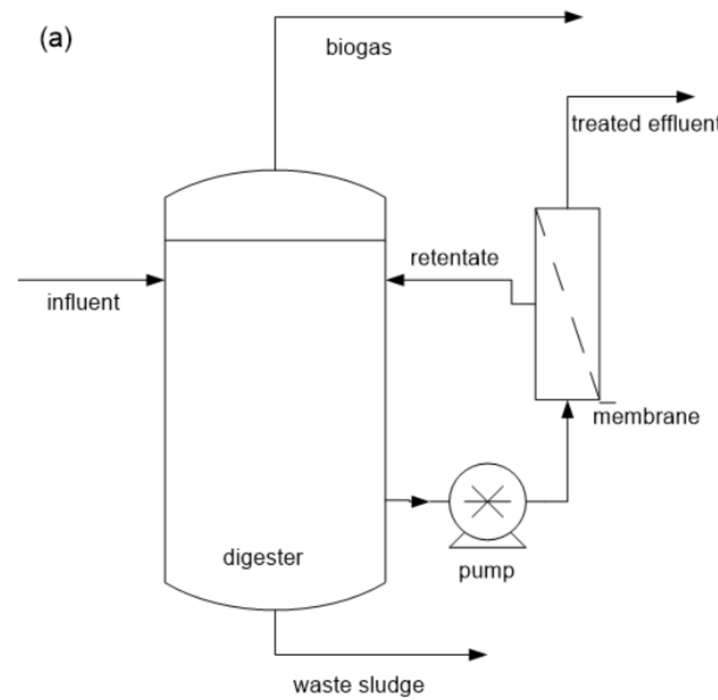
- Can be unheated
- High effluent quality

- High transmembrane pressure

→ energy input

- Membrane fouling

→ Scouring (cleaning), backwash, chemical treatment, replacement



Anaerobic Filter

- Can be upflow or downflow
- Separates SRT and HRT using biofilm grown on filter material
- Long start up for biofilm development
- Clogging, plugging

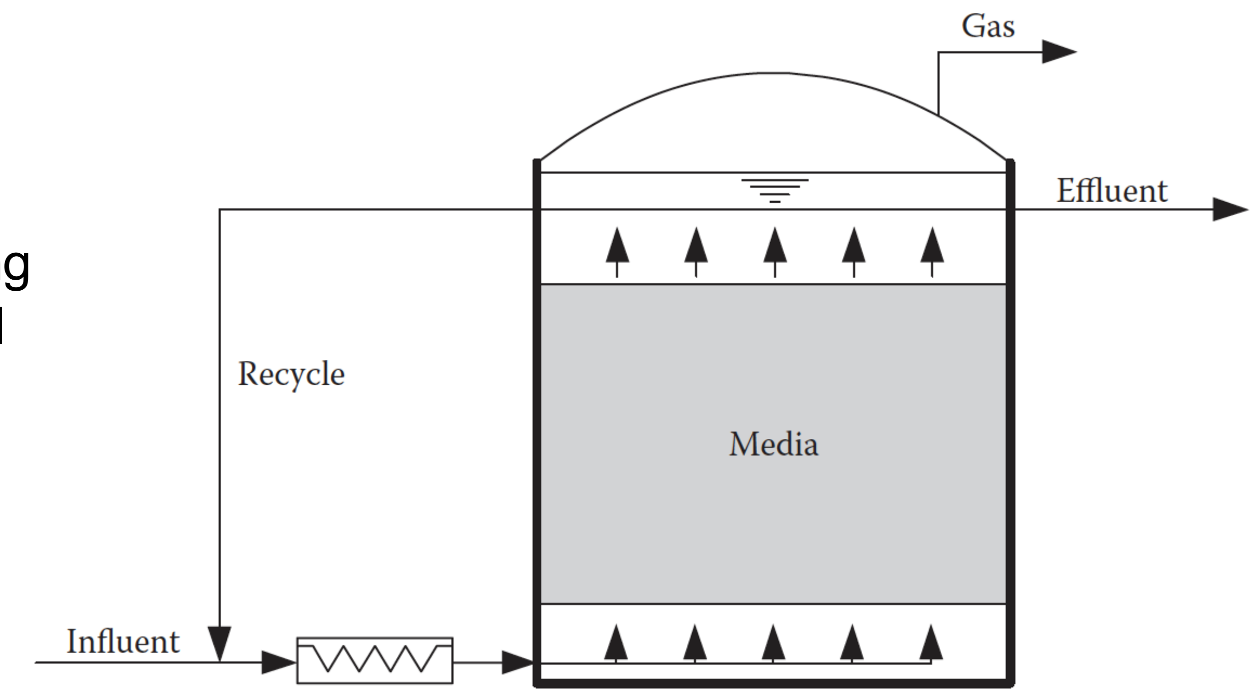


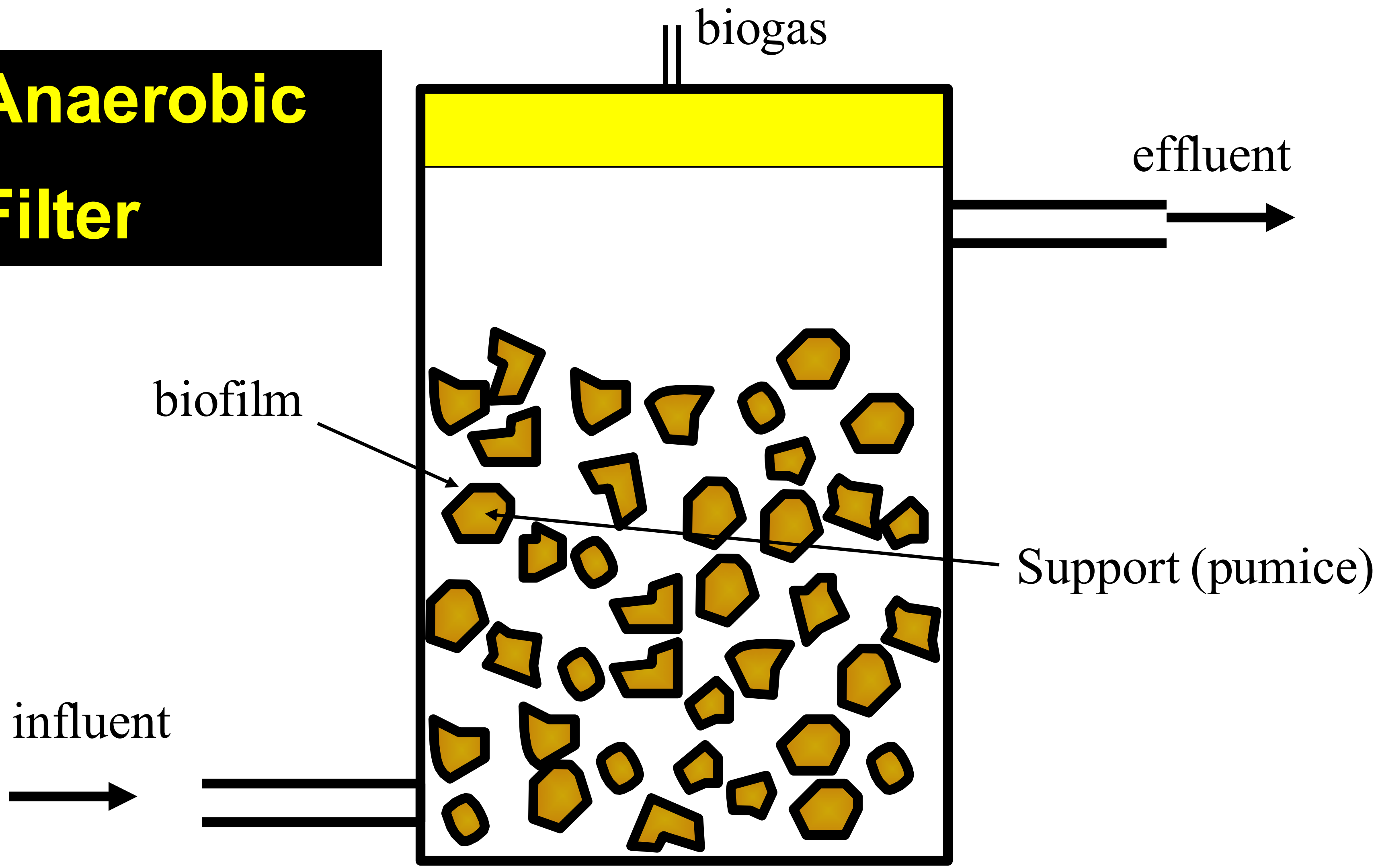
Figure 1.21. Anaerobic Filter

Immobilization of Active Biomass

Dilution Rate (1/HRT) Time > Max. growth Rate

sludge retention time uncoupled from hydraulic retention time

Anaerobic Filter



Upflow Anaerobic Sludge Blanket (UASB)

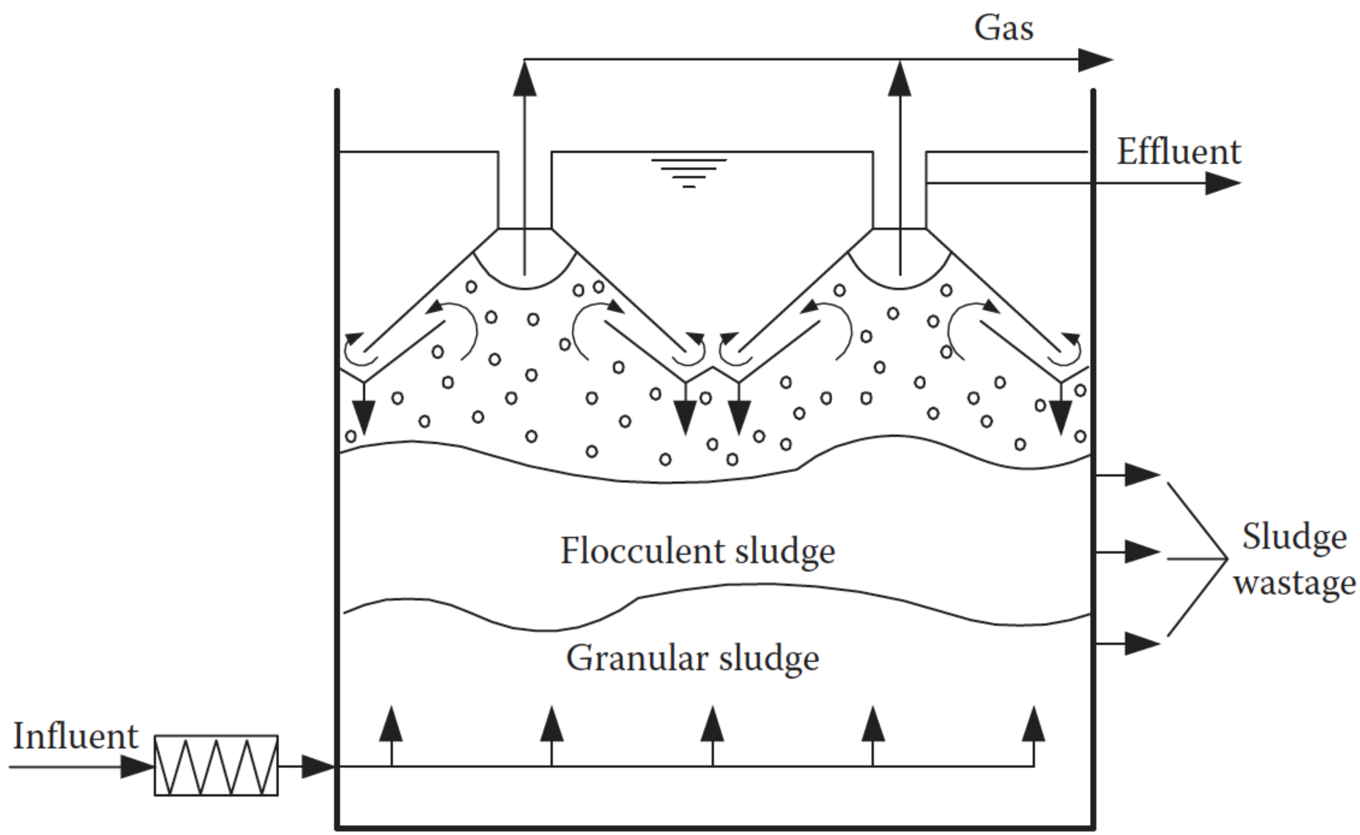
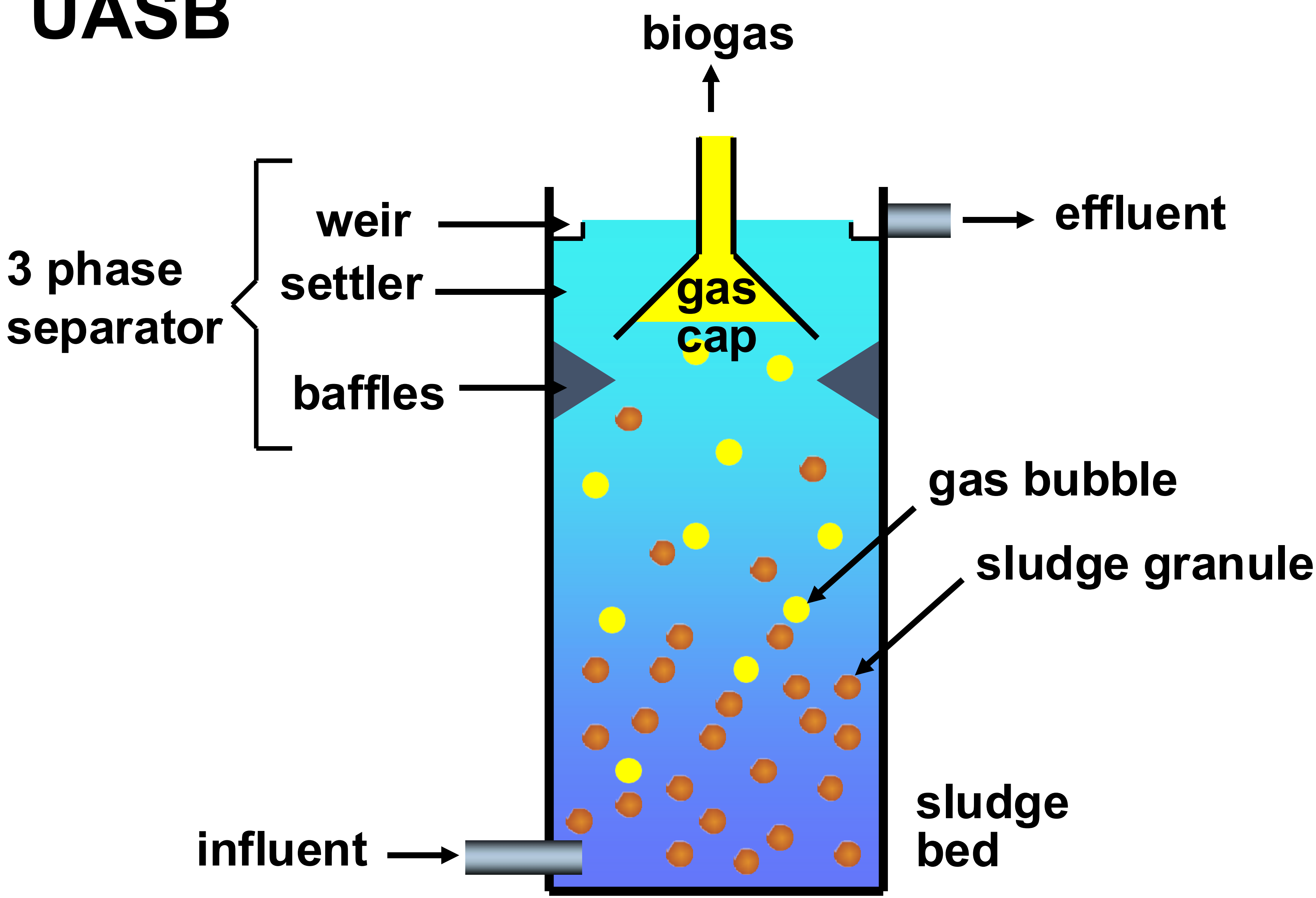


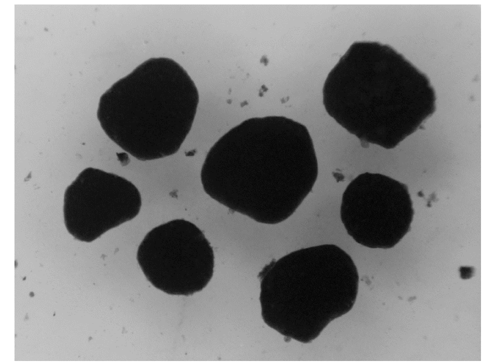
Figure 14.4. Upflow anaerobic sludge blanket (UASB) bioreactor

Upward-flow Anaerobic Sludge Blanket UASB



Upflow Anaerobic Sludge Blanket UASB and Expanded Granular Sludge Bed EGSB

- Rely on granular sludge
- High settling ability, excellent solids/liquid separation
- No biofilm attachment media is necessary
- High biomass concentrations (30,000-80,000 mg/L VSS)
- Need solids capture system to retain granules lost due to granule floating or change of upflow velocity.



Physical: dense compact biofilms high settleability

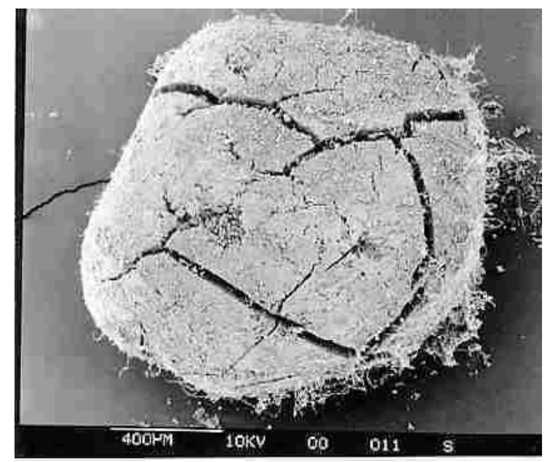
high mechanical strength

(30-80 m/h)

Microbial: balanced microbial community syntrophic partners

closely associated high methanogenic activity
(0.5 to 2.0 g COD/g VSS.d)

protection from toxic shock



SEM_SandGrainCrackedBiofilm.jpg
(Mike Dempsey)

Expanded Granular Sludge Bed (EGSB)
Anaerobic fluidized bed bioreactor (AFBR)

- Use carrier (sand, **GAC**) for biofilm development
- Has similar advantages and disadvantages as UASB/EGSB
- GAC – granular activated carbon, a desirable carrier
  - Irregular surface
  - Adsorption of substrates
- High biomass concentration

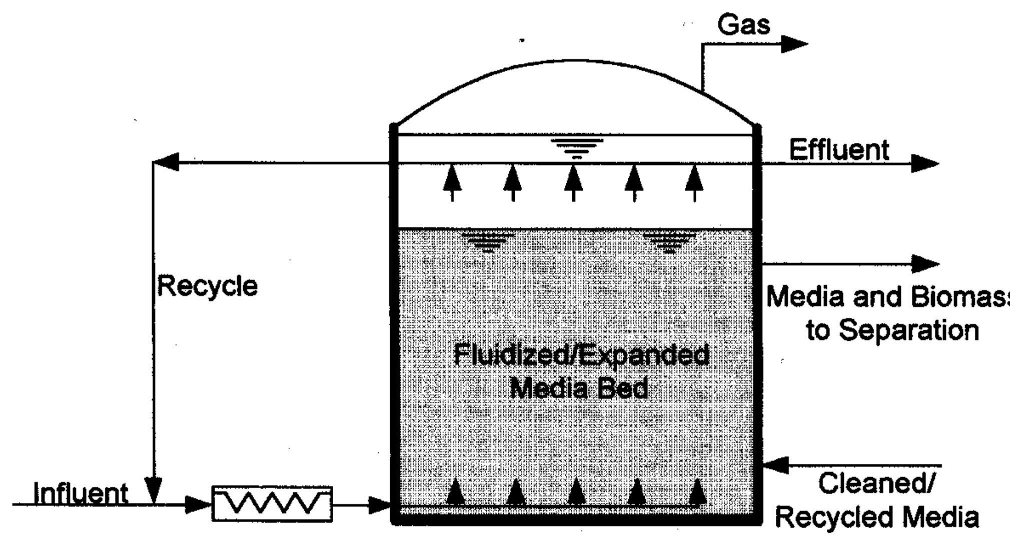
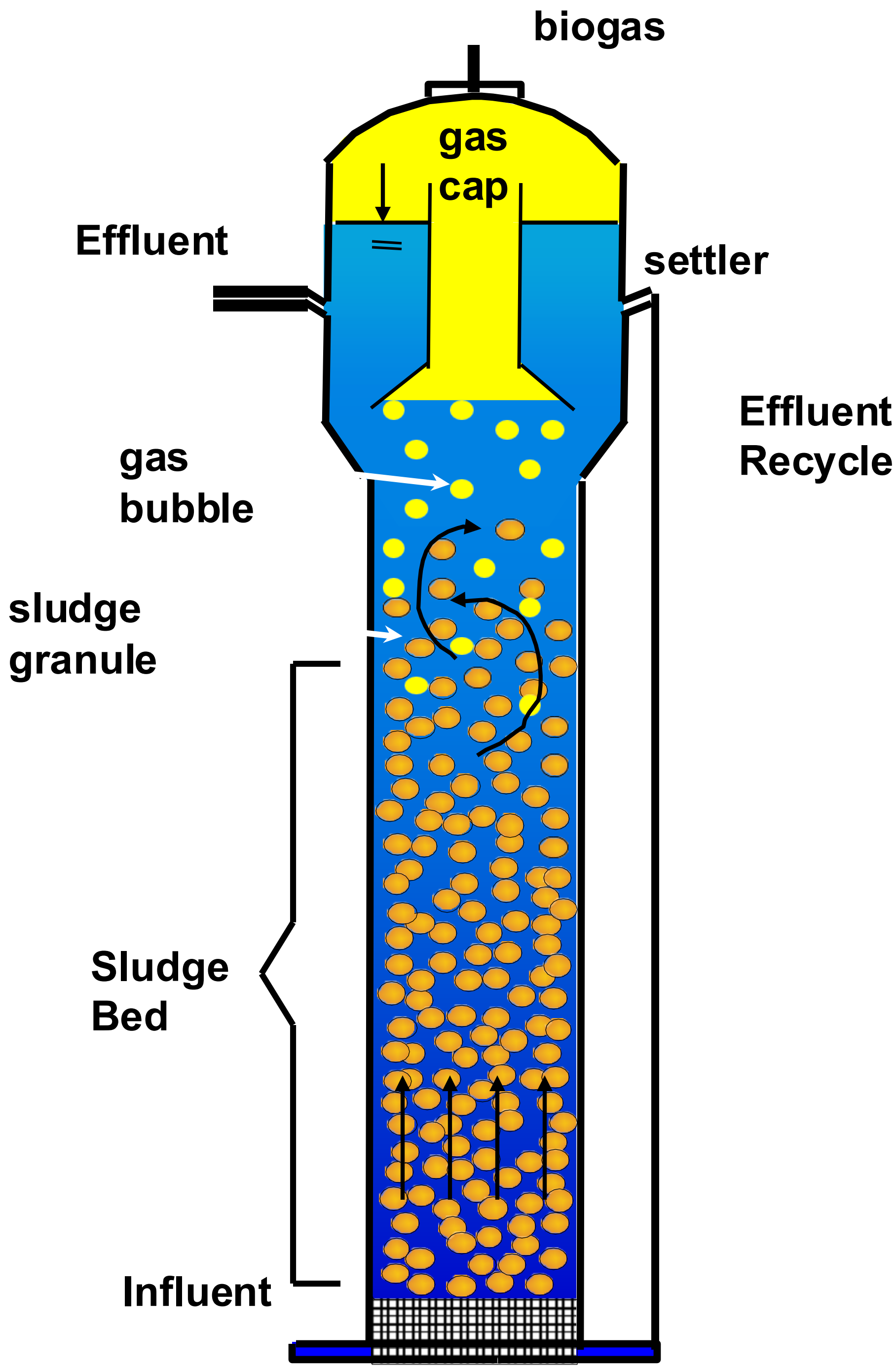
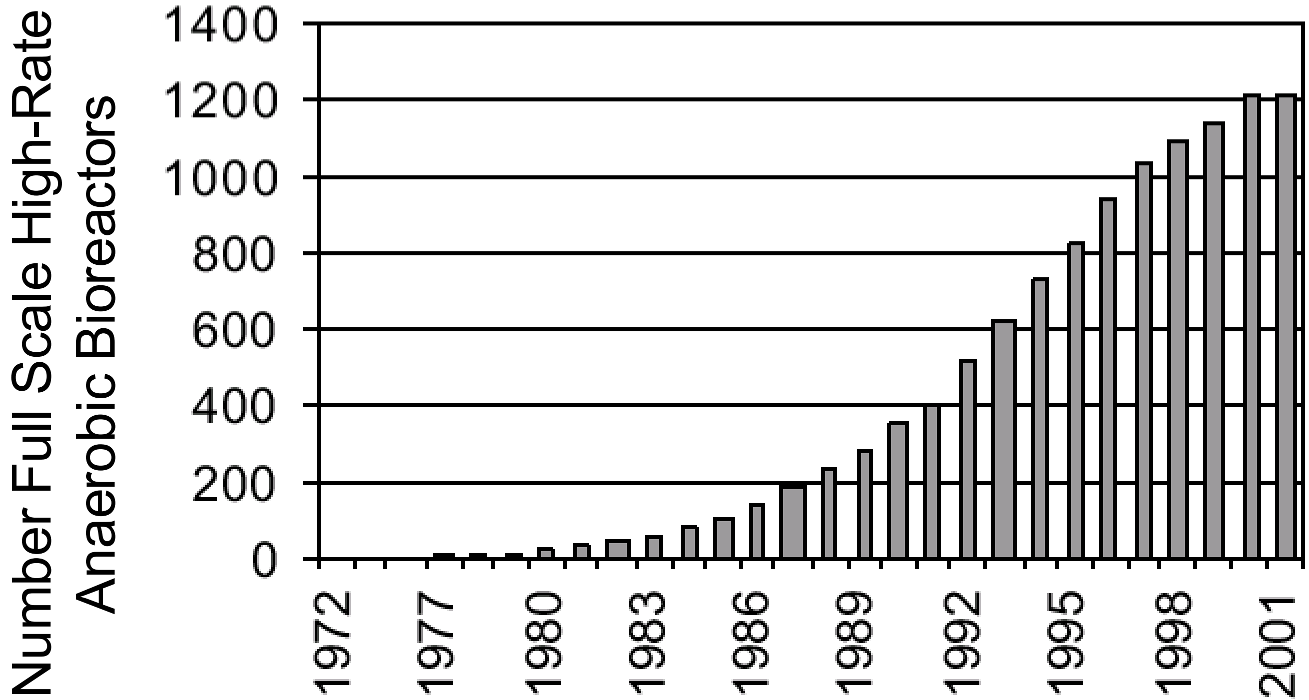


Figure 13.14 Fluidized bed and expanded bed process.

Expanded Granular Sludge Bed

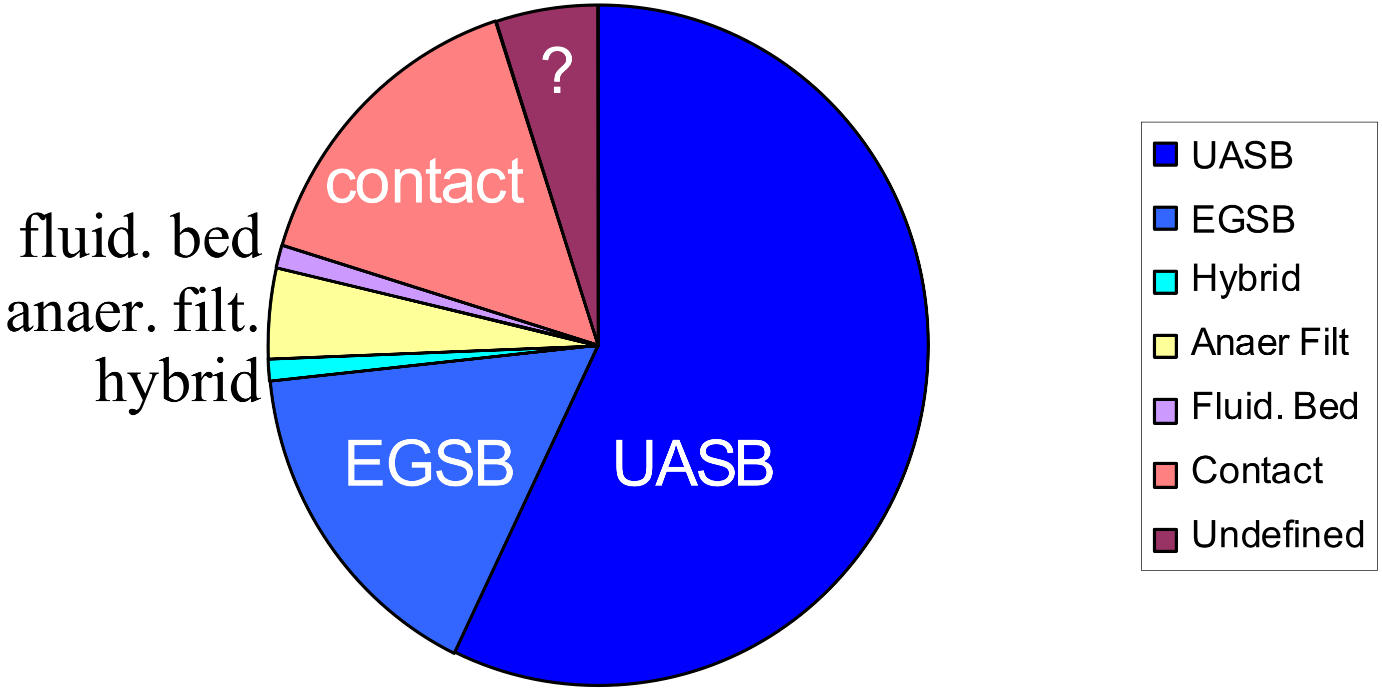


Surveyed High Rate Anaerobic Plants



Cumulative number of high rate anaerobic treatment plants for industrial applications

Market-Share Granular Sludge Reactors (a little outdated)



EGSB+UASB = 72%

Design Loads Full Scale
UASB & EGSB

reactor	n	average design load
UASB	682	10 kg $COD/m^3.d$
EGSB	198	20 kg $COD/m^3.d$

Removal Efficiency of Biodegradable COD 85 to >90%

Most Important Markets for High Rate Anaerobic Treatment

- Breweries and beverage industry
- Distilleries and fermentation industry
- Food Industry
- Pulp and paper

These four wastewater types account for 87% market

New and Emerging Markets for High Rate Anaerobic Treatment

- Chemical and Petrochemical
- Textile Industry Effluents
- Landfill Leachates
- Sulfate reduction coupled to sulfur removal
- Sulfate reduction coupled metal recovery

Temperature

Anaerobic reactions are slow and temperature sensitive

Mesophilic (30 – 38 °C)

Thermophilic condition (50 - 60 °C)

- faster hydrolysis – shorter HRT
- Inactivation of pathogens
- Heating can be costly

If heated, the typical SRT is 15 days, if unheated >40 days

pH

pH decreases as SCCAs are produced.

Methanogens are sensitive to environmental pH: 7-8 (6.6-7.6)

If there is not enough buffer, a sudden increase in loading rate can drop the pH

→ slow down methanogenesis

→ further accumulation of SCCAs

Solution:

add base/buffer (NaOH, KOH, $NaHCO_3$) but is costly

reduce loading rate

Light metal cations

Cation toxicity: Na^+, K^+, Ca^{2+}, Mg^{2+} at high concentration.

- E.g. Na^+ > 5000 mg/L, can be >15000 mg/L after acclimation
- Synergistic response
- Na^+, K^+, Ca^{2+} have antagonistic toxicity

SCCA (VFA) toxicity: ~1000 mg/L before acclimation

TABLE 14.5
Stimulatory and Inhibitory Concentrations of Light Metal Cations

	Concentration, mg/L		
Cation	**Stimulatory**	**Moderately Inhibitory**	**Strongly Inhibitory**
Sodium	100–200	3500–5500	8000
Potassium	200–400	2500–4500	12,000
Calcium	100–200	2500–4500	8000
Magnesium	75–150	1000–1500	3000

Note: Adapted from McCarty, P. L., Anaerobic waste treatment fundamentals. Public Works, 95 (9): 107–12; (10): 123–26; (11): 91–94; (12): 95–99, 1964.

Ammonia

- Required nutrient for microbial growth at low concentrations
- 50- 200 mg/L as N within stimulatory range and above is inhibitory
- Free ammonia (NH_3) cause toxic response >100 mg/L as N
- Reduce:
  - Temperature
  - pH
  - total ammonia concentration

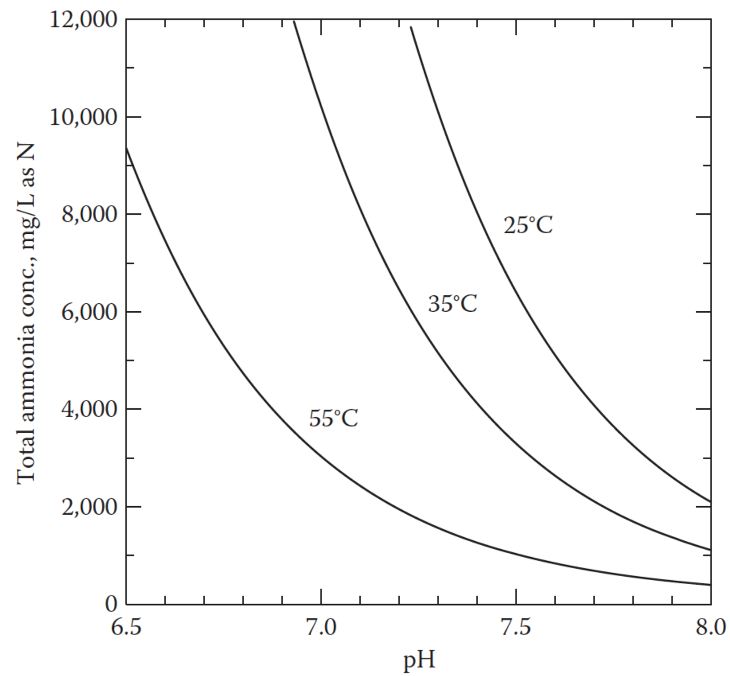


FIGURE 14.12 Effects of pH and temperature on the total ammonia-N concentration necessary to give a free ammonia concentration of 100 mg/L as N. The curves were generated from equilibrium and thermodynamic constants given in *Water Chemistry*. (Snoeyink, V. L. and Jenkins, D., John Wiley & Sons, Inc., New York, 1980).

Sulfide

- Produced through the reduction of sulfur-containing organic matter (proteins)
- >200 mg/L causes inhibition and 100-200 after acclimation
- Sulfate: alternate electron acceptor that competes with methanogens for available electrons in organic matter.
  - Formation of H_2S: corrosive, odor
  - Reduces methane
- Solution: precipitate as iron sulfide

Trace metals

Fe, Co, Ni, Zn, Cu, Mn, Mo, Se

Required as components of enzymes

But can be toxic at higher level

TABLE 14.7
Soluble Heavy Metal Concentrations Exhibiting 50% Inhibition of Anaerobic Digesters

Cation	Concentration mg/L
Fe^{+2}	1–10
Zn^{+2}	10^{-4}
Cd^{+2}	10^{-7}
Cu^{+}	10^{-12}
Cu^{+2}	10^{-16}

Note: Adapted from Mosey, F. E. and Hughes, D. A., The toxicity of heavy metal ions to anaerobic digestion. Water Pollution Control, 74:18–39, 1975.

Nutrients

- Reduced nutrient requirements
- 4-10% of COD removed is converted to biomass
- Available in the waste being treated
- Needed when treating carbon-rich industrial waste(water)

Mixing

- Mixing is important to maintain uniform SRT, temperature, substrates, and inhibitors
- Efficient mixing can be challenging due the high solids
- Types of mixing
  - Gas recirculation
  - Mechanical mixing
  - Liquid recirculation

Waste Type

Primary COD Form:
In PS:
Raw, particulate organic matter (fats, fibers, proteins).

In WAS:
Microbial cell walls and EPS (Extracellular Polymeric Substances).

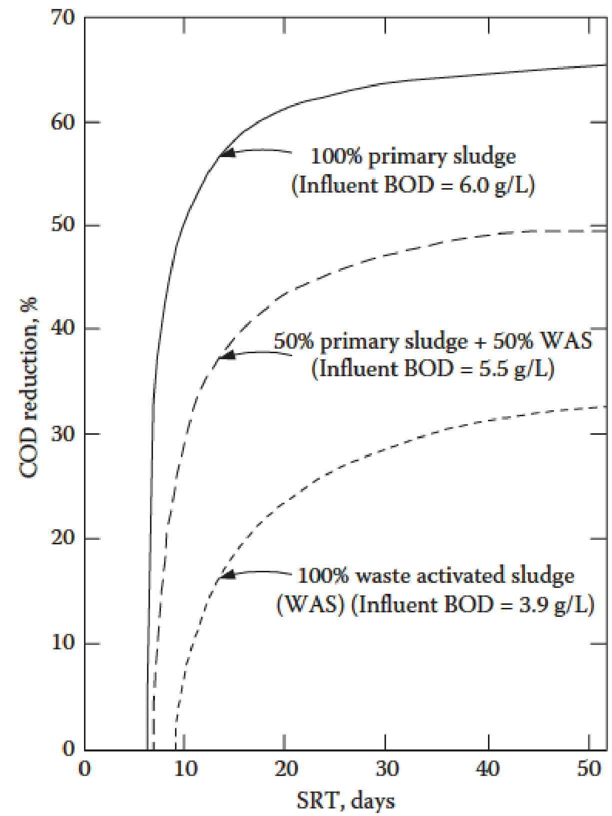
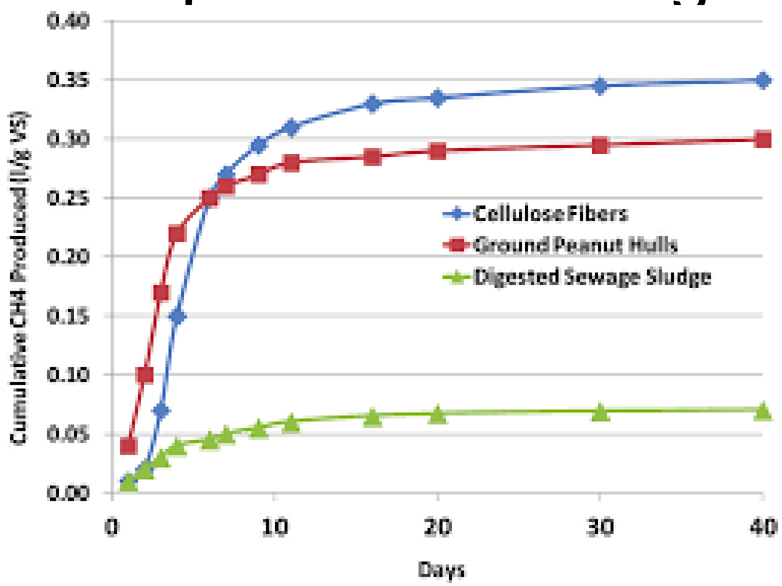
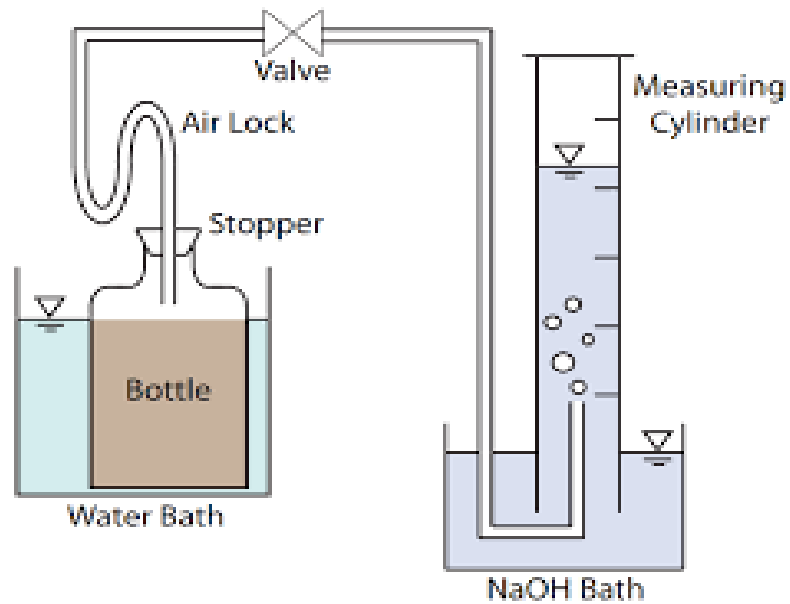


FIGURE 14.13 Effect of SRT on the stabilization of primary solids and waste activated sludge (WAS). (From Parkin, G. F. and Owen, W. F., Fundamentals of anaerobic digestion of wastewater sludges. *Journal of the Environmental Engineering Division, ASCE,* 112:867–920, 1986. Copyright © American Society of Civil Engineers. Reprinted with permission.)

Biochemical methane potential assay

BOD – how much organic material can be degraded in an aerobic process
BMP – anaerobic equivalent of BOD: how much methane can be produced biologically





Methane production, collection and use

Biogas: 65–70% CH_4 + 30-35% CO_2+small amount of H_2, N_2, H_2S, H_2O

From stoichiometry calculations: 1 kg COD → 0.35 m^3 CH_4 (STP)
Heating value of CH_4: 35800 kJ/m^3 (STP)

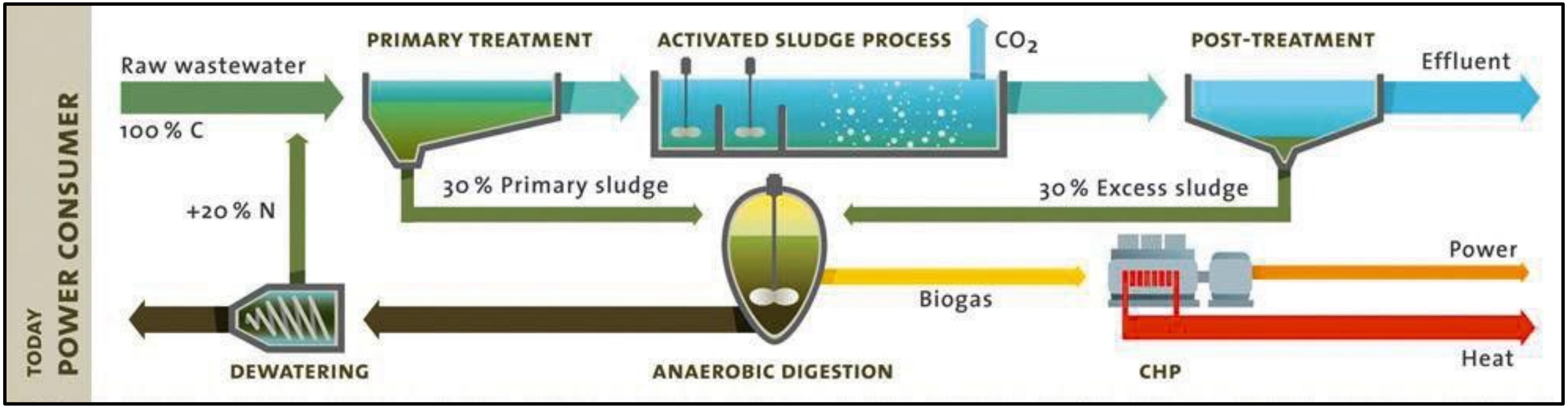
Biogas utilization – combined heat and power (CHP), flare
Biogas collection: float, fixed
The effluent is usually saturated/supersaturated with CH_4 lost to atmosphere

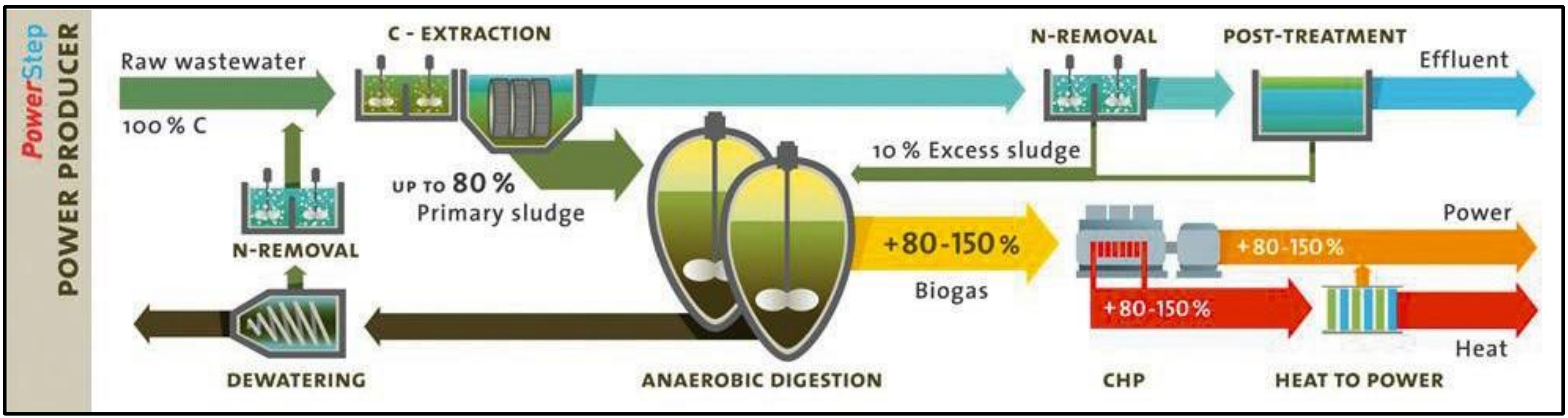
From “STEP” to “StaRRE”

STEP - Station d’épuration des eaux usées (WWTP)
StaRRE – Station de récupération des ressources de l’eau (**water resource recovery facilities** – WRRF)

in the framework of
circular economy

Powerstep (EU project)



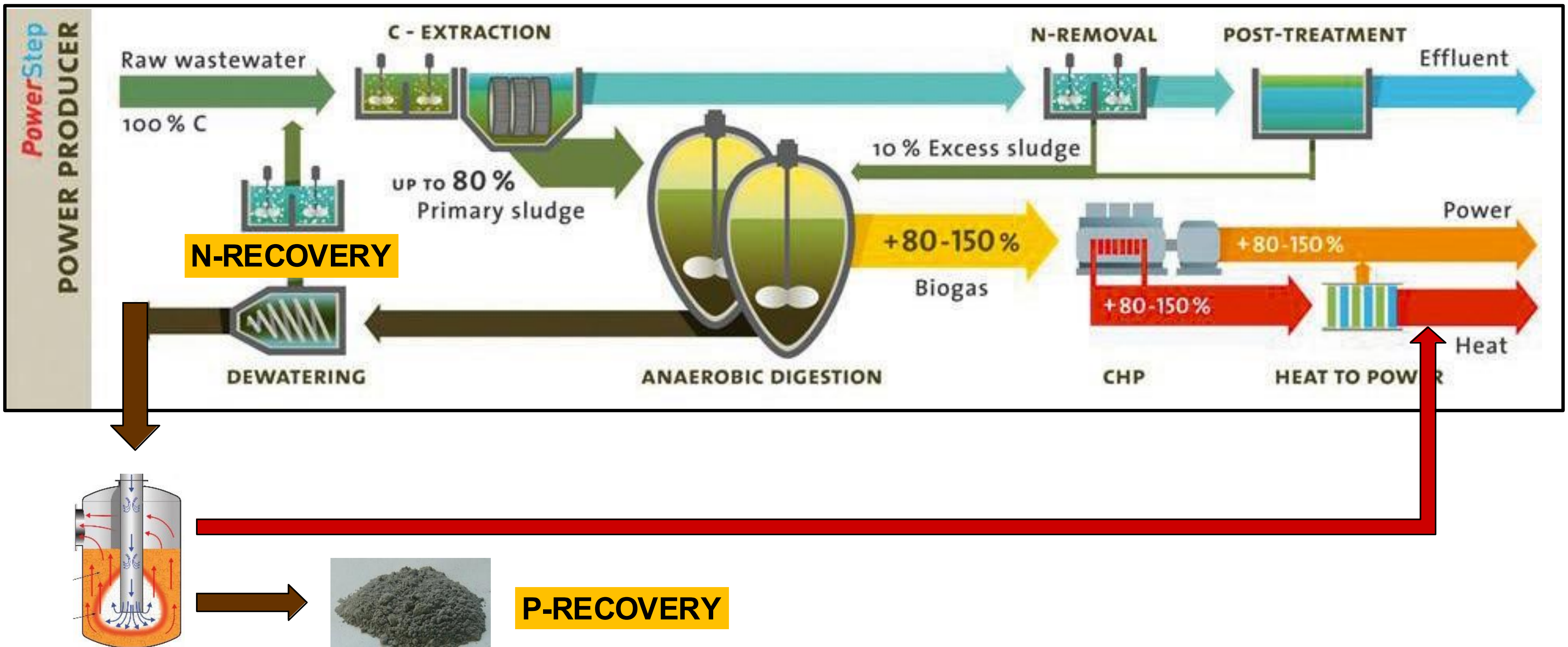


Phosphorous – a valuable resource in waste sludge

From 2026, the phosphorus from wastewater, sewage sludge or their ash must be recovered and upgraded

- The environmental authorities have decided to phase out waste sludge spreading in 2003 - and since 2006 all waste sludge has been incinerated.
- 64% is disposed of in sludge incineration plants, 14% in household waste incineration plants and the remaining 22% in cement factories.
- The 783 **Swiss wastewater treatment plants produce nearly 5,700 tonnes of phosphorus each year**, which could be recovered and thus **meet the needs of agriculture with a native source**.
- Switzerland imports nearly 15,000 net tonnes of phosphorus each year, of which 4,200 in the form of mineral fertilizers, 6,200 as fodder and 2,600 as food.

Powerstep & N,P-Recovery



Acid Leaching Methods (Wet Chemical)

Ammonia stripping from AD digestate effluent

The Reaction: This high pH shifts the equilibrium, converting the ammonium ions into volatile **ammonia gas** ($\mathrm{NH_3}$). High temperatures also favor this conversion.

$$\mathrm{NH_4^+ + OH^- \rightleftharpoons NH_3(gas) + H_2O}$$