Aalto University
School of Engineering

Biological treatment processes of water and waste
Lecture 6

WAT - E2180

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Lecture outline

Biological growth

Kinetics

Advanced process design

BACTERIA GAME

Dynamic nitrogen removal process

Storage processes

Storage polymers

Applications

Biological phosphorus removal

Removal mechanism

Existing process configurations

Anaerobic processes

Anaerobic digestion

Fermentation

Biological processes - growth

Cell growth

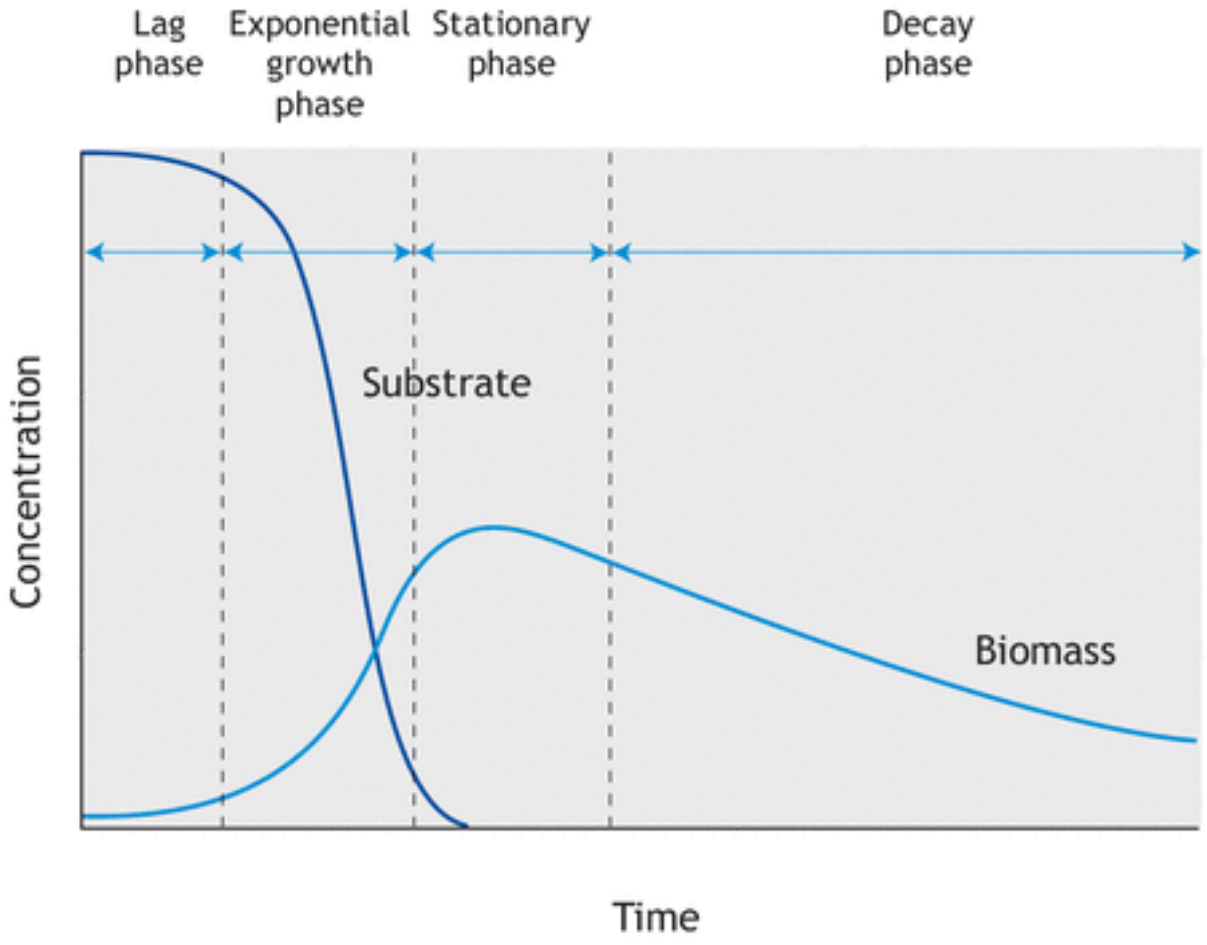


Figure 2.16 Biomass growth in batch mode (adapted from Metcalf & Eddy, 2003)

Microbial growth

Growth can be described with the equation:

$$r_{V,XB} = \mu_{max}\ f(S)\ X_B$$

Where

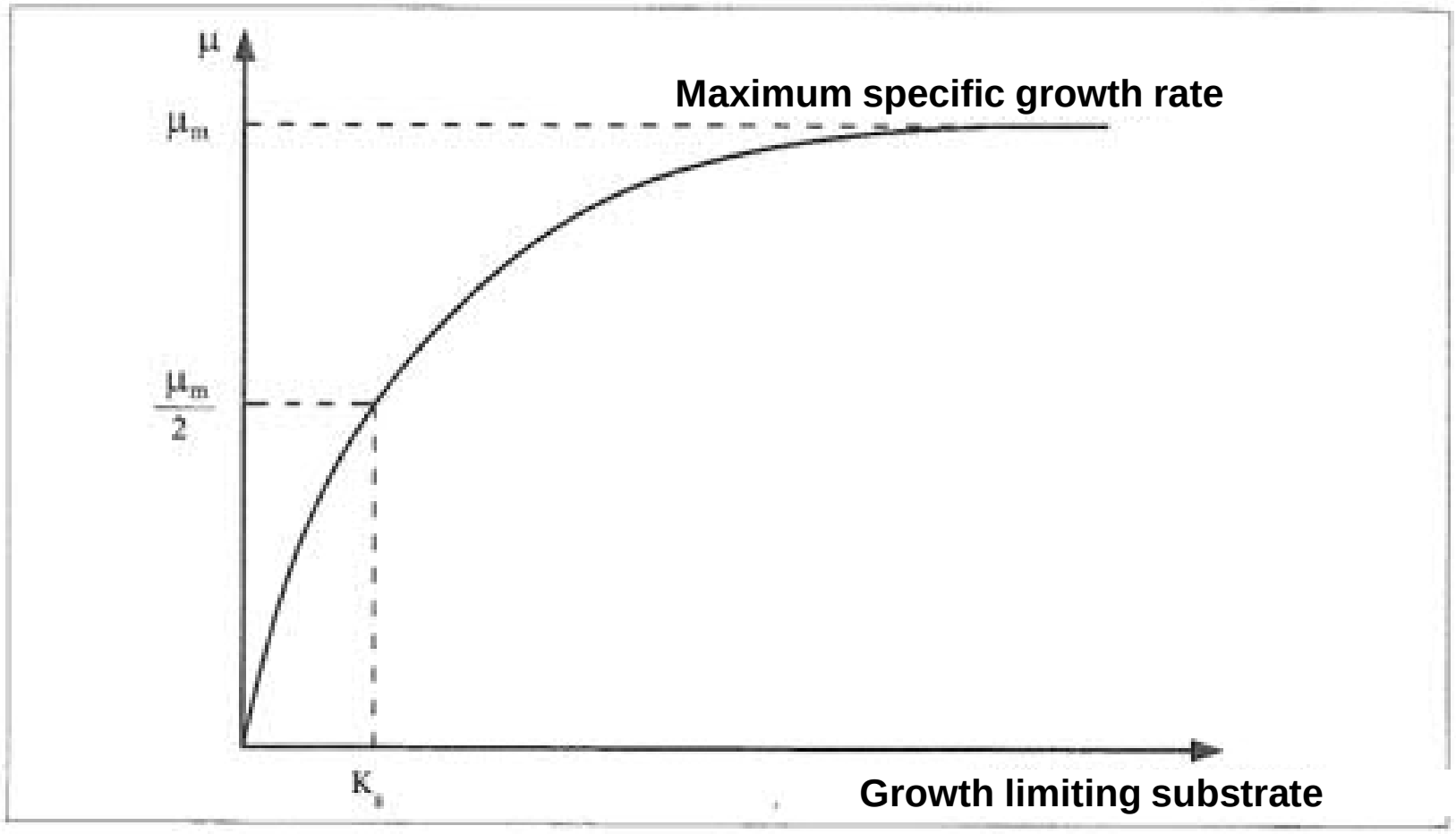
$r_{V,XB}$ = growth per unit of volume and time (e.g. kgCOD/m^{3}d)

μ_{max} = max specific growth rate (1/h or 1/d)

f(S) = growth kinetic function (depending on substrate), typically Monod

X_B = biomass concentration (kgCOD/m^3 or kgVSS/m^3)

Monod's kinetics



Bacterial growth

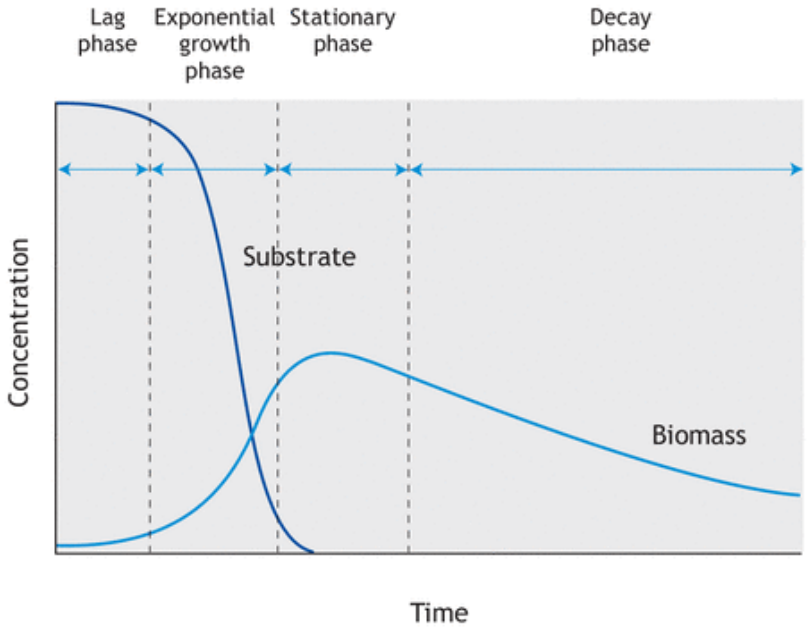


Figure 2.16 Biomass growth in batch mode (adapted from Metcalf & Eddy, 2003)

$$r_{V,XB} = \mu_{max} \cdot \frac{S}{S + K_S} \cdot X_B$$

$$r_{V,S} = \frac{\mu_{max}}{Y_{max}} \cdot \frac{S}{S + K_S} \cdot X_B$$

The growth of biomass depends on the substrate consumption (with a yield) and on the decay rate b

$$r_g = Y\ r_s - b\ X$$

Substrate consumption

$$r_{V,S} = r_{V,B} / Y_{max}$$

Y_{max} = maximum yield (kgCOD(B)/kgCOD(S) or kgVSS(B)/kgCOD(S)

Yield shows how much of the consumed substrate is transformed into new biomass in the reaction.

Note also Y_{obs} which is smaller than Y_{max}

Monod kinetics

$$r_{V,XB} = \mu_{max} \cdot \frac{S}{S + K_S} \cdot X_B$$

For biomass growth (g/m³d)

$$r_{V,S} = \frac{\mu_{max}}{Y_{max}} \cdot \frac{S}{S + K_S} \cdot X_B$$

For substrate consumption (g/m³d)

$$\mu_{obs} = \mu_{max}\, S / (S + K_s) \quad [1/d]$$

Observed specific growth rate

Taking into account the growth conditions

Oxygen:

$$\mu_{obs} = \mu_{\max} \cdot \frac{S_{O2,2}}{S_{O2,2} + K_{S,O2}}$$

$$\mu_{obs} = \mu_{\max} \cdot \frac{S_2}{S_2 + K_S} \cdot \frac{S_{O2,2}}{S_{O2,2} + K_{S,O2}}$$

Temperature:

$$\mu_{\max(T)} = \mu_{\max(20°C)} \cdot e^{K(T-20)}$$

Typical values for stoichiometric and kinetic parameters

Table 2.9 Typical values of stoichiometric (f_S^0, Y) and kinetic (q_{max}, μ_{max}) parameters for various bacterial groups, (adapted from Rittmann and McCarty 2001)

Electron donor		Electron acceptor	f_S^0	Y	μ_{max}	K
Microbial group	e^- donor					
Chemotrophic organotrophs						
Aerobic heterotrophs	Sugar	O_2	0.70	0.49 gVSS/gbCOD	13.2	27.0 g bCOD/gVSS.d
Aerobic heterotrophs	No sugar	O_2	0.60	0.42 gVSS/gbCOD	8.4	17.0 g bCOD/gVSS.d
Denitrifiers	Organic	NO_3^-, NO_2^-	0.50	0.25 gVSS/gbCOD	4.0	16.0 g bCOD/gVSS.d
Fermenting organisms	Sugar	Organic	0.18	0.18 gVSS/gbCOD	1.2	10.0 g bCOD/gVSS.d
Sulphate reducers	Acetate	SO_4^{2-}	0.08	0.057 gVSS/gbCOD	0.5	8.7 g bCOD/gVSS.d
Methanogens (acetoclastic)	Acetate	Acetate	0.05	0.035 gVSS/gbCOD	0.3	8.4 g bCOD/gVSS.d
Chemotrophic lithotrophs						
Nitrifiers :AOB	NH_4^-	O_2	0.14	0.34 gVSS/gNH_4-N	0.9	2.7 g NH_4-N /gVSS.d
Nitrifiers :NOB	NO_2^-	O_2	0.10	0.08 gVSS/gNO_2-N	0.5	1.1 g NO_2-N/gVSS.d
Methanogens (hydrogenotrophic)	H_2	CO_2	0.08	0.45 gVSS/gH_2	0.3	1.1 g H_2/gVSS.d

bCOD: biodegradable COD

μ_{max} in gVSS /gVSS d

$k = \mu_{max}/Y$= specific r_{max} (per unit biomass)

Denitrification rate

$$r_{V,NO} = \left(\frac{1 - Y_H}{2.86 Y_H}\right) \mu_{max,H} \left(\frac{S_{BOD}}{K_{COD} + S_{COD}}\right) \left(\frac{S_{NO}}{K_{NO} + S_{NO}}\right) \eta_g X_{b,h}$$

where

$r_{V,NO}$ = reaction rate per unit volume nitrate- and nitrite-nitrogen,
Y_H = biomass yield coefficient,
$\mu_{max,H}$ = maximum specific growth rate of heterotrophs,
S_{COD} = soluble material concentration organic substrate,
K_{COD} = half-saturation coefficient organic substrate,
S_{NO} = soluble material concentration nitrate- and nitrite-nitrogen,
K_{NO} = half-saturation coefficient nitrate-nitrite,
η_g = correction factor for μ_H under anoxic conditions, and
$X_{b,h}$ = particulate material concentrations.

Design of biological processes

:

DEMO 1

Average daily flow rate	37 850 m3/d
Influent water:	
BOD7	140 mg/l
Ammonium-N	35 mg/l
Suspended solids Of which unbiodegradable	90 mg/l 30 mg/l
Effluent water:	
BOD7	10 mg/l
Ammonium-N	0,5 mg/l
Total N	10 mg/l
Suspended solids	15 mg/l
Temperature	12 C
MLVSS/MLSS	0,8
MLVSS	2,4 g/l
Y (heterotrophs)	0,6 kg VSS/kg BOD
b (12 C)	0,044 d-1
Y (nitrifiers)	0,12 kg VSS/kg NH4-N
bN (12 C)	0,06 d-1

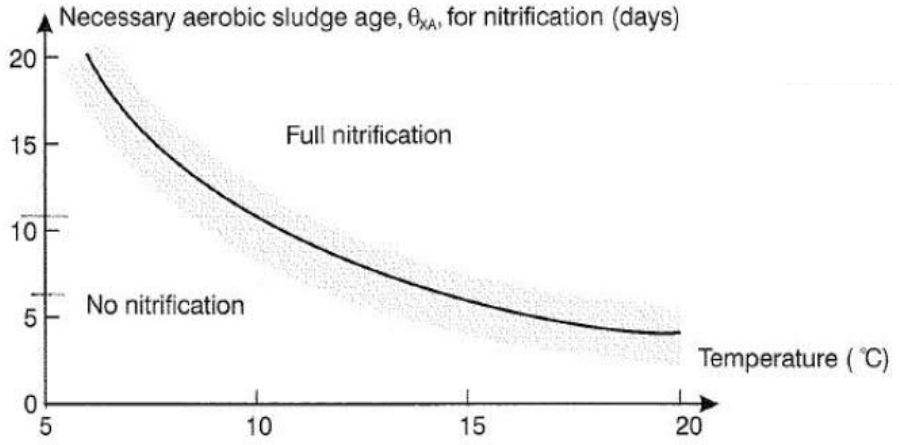
Dimension an activated sludge process where full nitrification and 70% denitrification is achieved.

Use the denitrification rate (12 ° C, raw WW) of 1,5 gN/kgVSSh

Assumption 1: No nitrate in the influent water

Assumption 2: No denitrification in the secondary clarifiers.

DEMO 1



Dimensioning of nitrifying process:

- **Choose SRT→ nitrification**

12 ° C → 10 d

- **Calculate the needed biomass per day:**
- **Biomass XV** $= \frac{YQ\,(So-Se)}{1+b\theta c} + \frac{Y_n Q\,(S_{NH4}-Se_{NH4})}{1+b_n \theta c} =$

2031,2 + 97,0 = 2128 kgVSS/d

- **Biomass (VSS → SS) = 2660 kgSS/d**
- **Inert particulate influent 1136 kgSS/d → Total sludge amount SS = 3796 kgSS/d, sludge concentration 3 g/l**
- **Reactor volume needed= (sludge amount x SRT) / X = 12653 m3**

NOTE! This calculation is simplified → inert SS produced not considered

DEMO 1

The volume needed for denitrification is calculated based on the denitrification rate.

Total N 70 % → to be denitrified 927 kg/d = 38,6 kgN/h = 38 600 gN/h

Denitrification rate (12C, raw WW)→ 1,5 gN/kgVSS/h

MLVSS 2,4 g/l → needed volume 10 722 m^3

Removal in biological processes

Removal	Conditions	When
Organic matter	Aerobic, short SRT	Focus on removal
Organic matter	Anaerobic, long HRT&SRT	for high strenght waters, focus on energy recovery
Ammonium (nitrification)	Aerobic, long SRT	Well known process
Total nitrogen Nitrification + denitrification	Aerobic + anoxic zones, Short/long SRT	Well known process
Total nitrogen Short-cuts	Low DO (nitritation + denitritation) Deammonification	Focus on energy savings High strength waters
Phosphorus	Aerobic + anaerobic zones	P reuse, sludge production, carbon source
NOM, iron, manganese, organic micropollutants	Aerobic, mainly long SRT	Often cost effective solution

Design approaches for biological processes

Sludge age (days) → Sludge age selected on the basis of process goals (e.g. nitrification) → Basin volume

Sludge loading (kgBOD/kgMLSSd) → As above but does not take into account differences in sludge yield (e.g. process design when water is very typical)

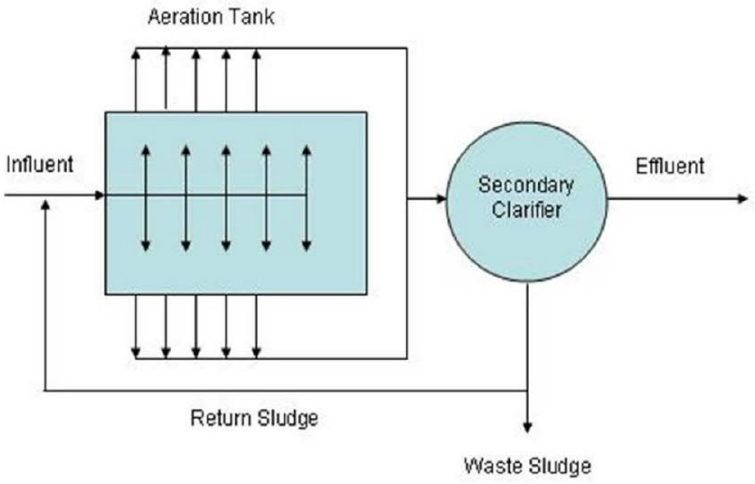
Volumetric loading (kgBOD/m^3d) e.g. rough estimations for bugdeting

Surface loading (kgBOD/m^2d or kgN/m^2d) MBBR and biological filters

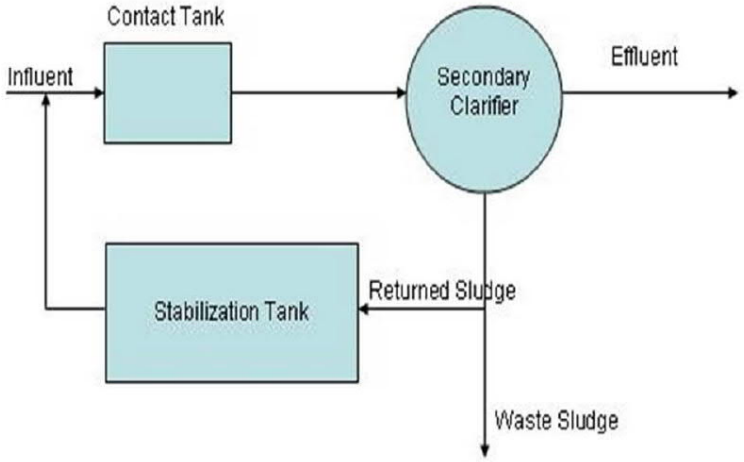
Reaction rate (gN/gMLSSh) e.g. anoxic zones

Hydraulic retention time (hours) e.g. anaerobic and anoxic zones

Important design aspects

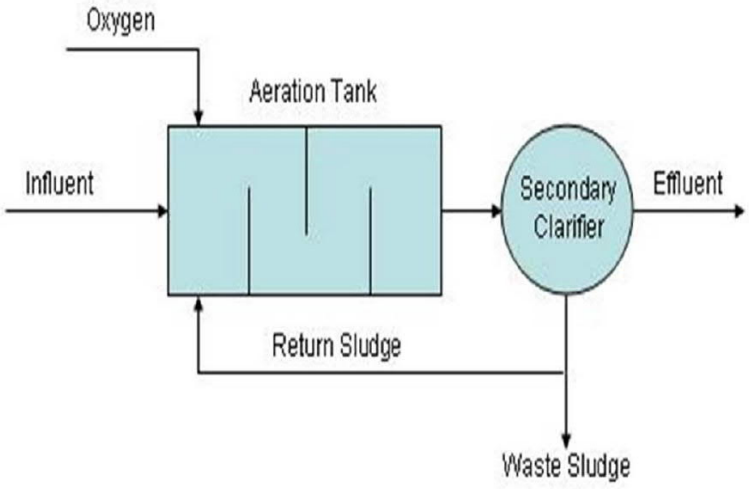


Complete Mix Activated Sludge Process

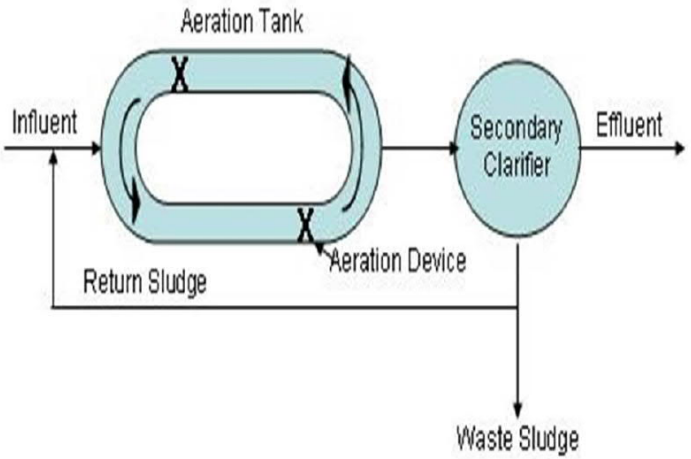


Contact Stabilization Activated Sludge

Intensive or extended aeration

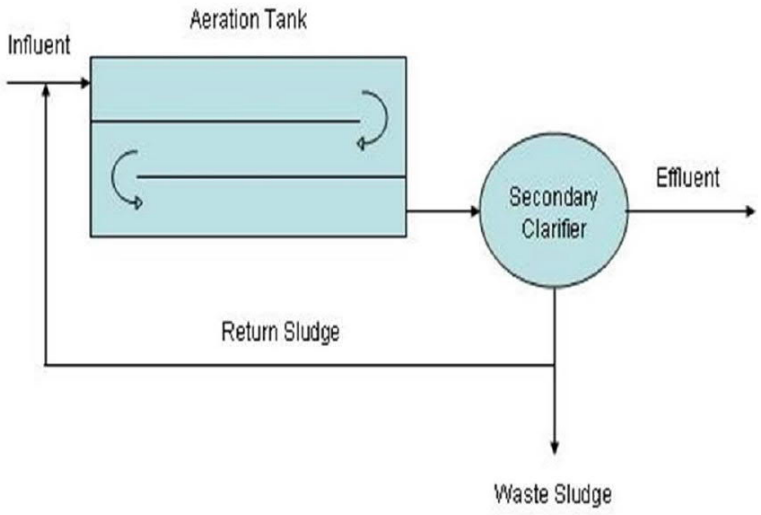


High Purity Oxygen Activated Sludge

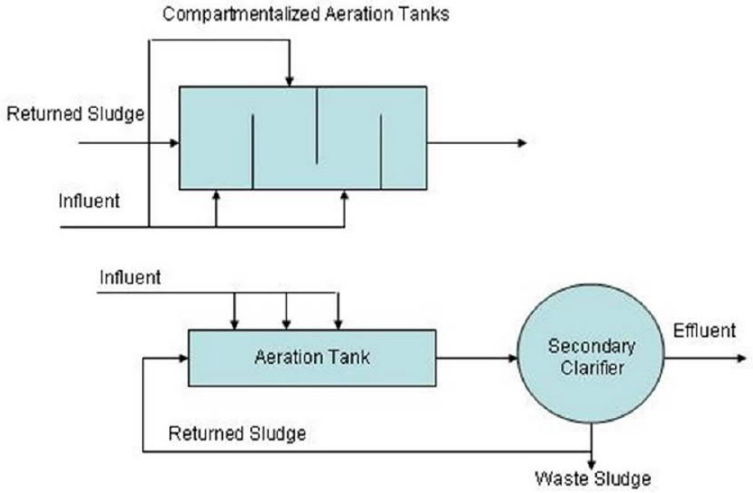


Oxidation Ditch Activated Sludge Process

Process configurations

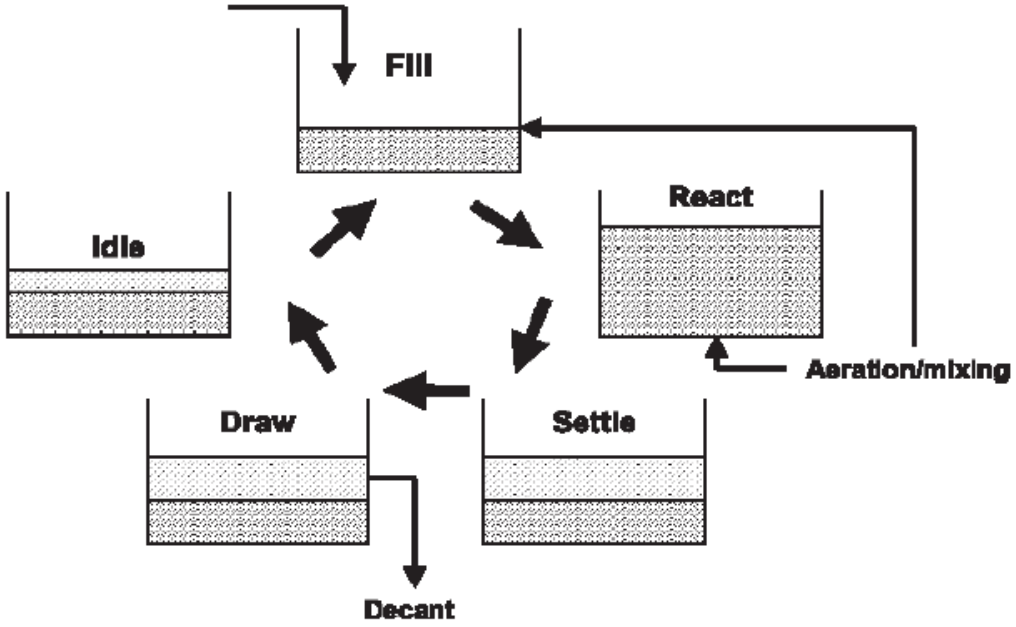


Plug Flow Activated Sludge Process



Step Feed Activated Sludge Process

Process configuration



Sequencing batch reactor

All reactions happen in the same volume

Typically 2 or 3 parallel SBRs

Process type

Activated sludge

Moving bed bioreactor (MBBR)

Membrane bioreactor (MBR)

Biological filters

Aerobic granular sludge (AGS)

Selection depends on wastewater characteristics, climate conditions, energy aspects, effluent requirements, size etc.

Nitrogen and phosphorus removal

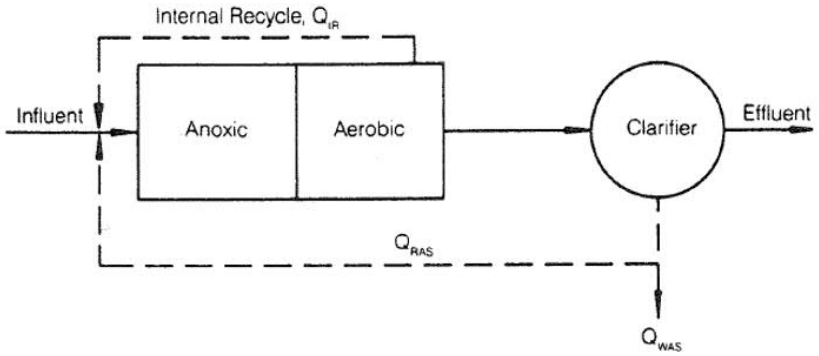


Figure 8.9 Modified Ludzack–Ettinger process for nitrogen removal (WAS = waste activated sludge).

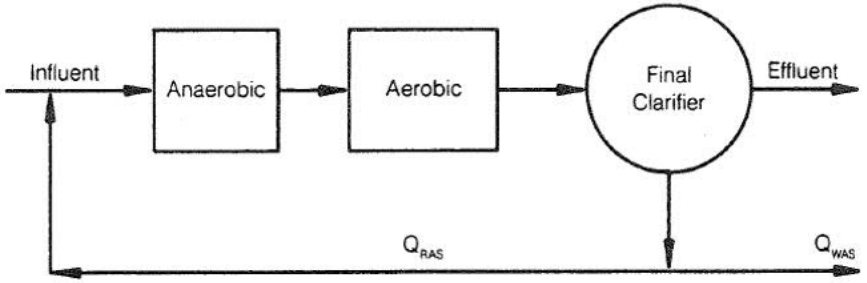


Figure 8.3 The A/O process (RAS = return activated sludge, WAS = waste activated sludge).

Alternative configurations

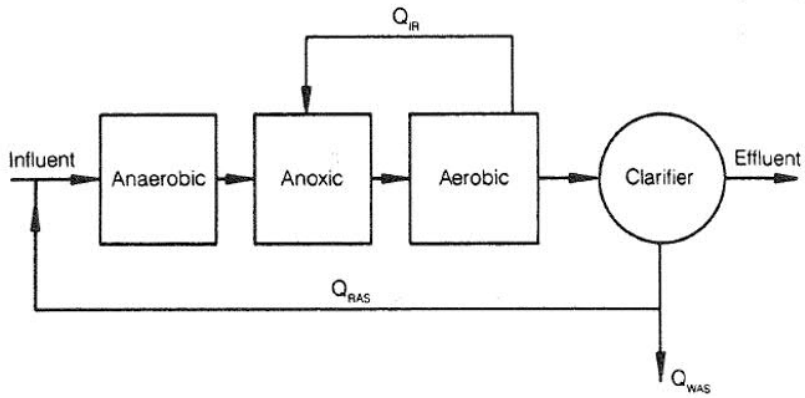


Figure 8.14 A^2/O process for phosphorus removal (WAS = waste activated sludge).

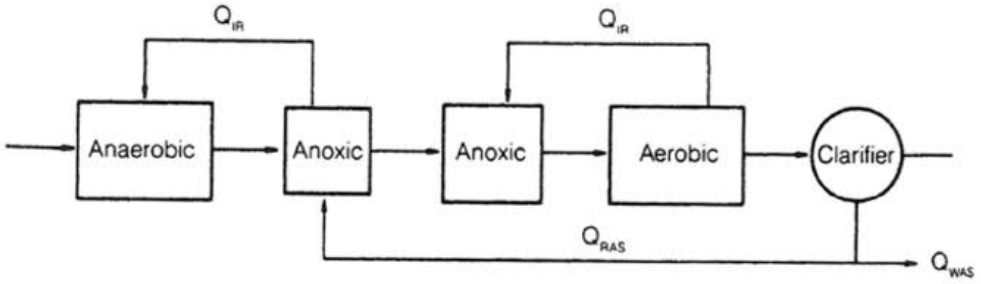


Figure 8.15 Modified University of Cape Town process for phosphorus and nitrogen removal (WAS = waste activated sludge).

How to calculate the recycle ratio of RAS?

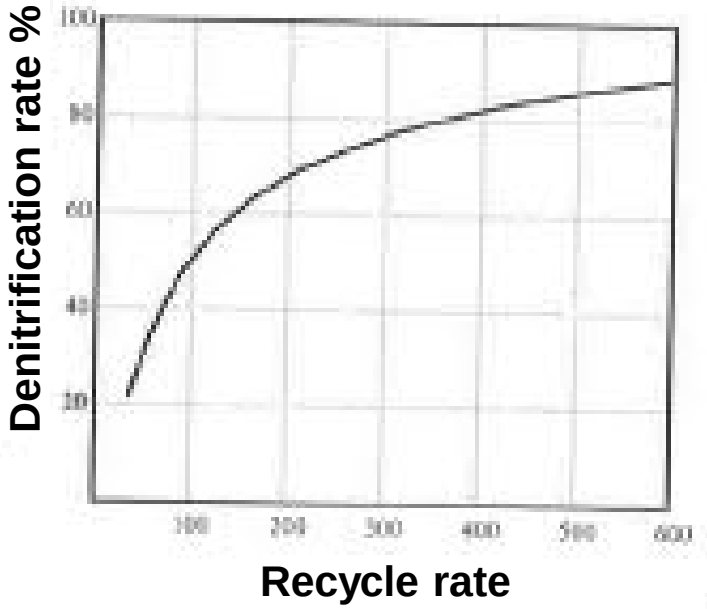
Recycle ratio = 100X / ((1200/SVI) - X)

Where X = MLSS (g/l)

And SVI = sludge volume index (ml/g)

Recycle must be sufficient for denitrification

Typical recycle ratio 100 - 200 %



BREAK

BACTERIA GAME: Advanced version 2 Dynamic nitrogen removal process ☺

- **First test the process with ND configuration**
- **Each player picks a type of microbe and places it in suitable conditions in the process**
- **ZONE 1:**
  - Each player picks two wastewater constituent. This is the influent wastewater that enters the first zone.
  - Try to form suitable sets for your microbe's reaction using influent wastewater and zone conditions.
  - When a reaction occurs, select the correct end-products
  - Check if possible reactions exist with the end-products
- **ZONE 2:**
  - Move the wastewater constituents and the end-products that have not yet reacted to zone 2.
  - Repeat the steps from zone 1.
- **RAS flow**
  - Move the wastewater constituents and the end-products that have not yet reacted to zone 1 via RAS flow.
  - Repeat the steps from above.
- **GAME ENDS WHEN ALL THE REACTIONS HAVE OCCURRED.**

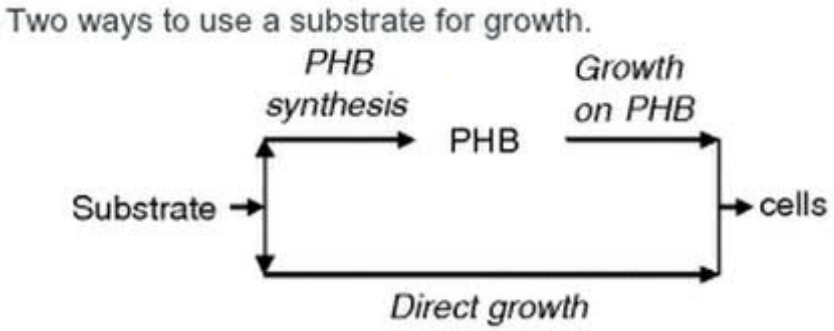
BACTERIA GAME: Advanced version 2 Dynamic nitrogen removal process ☺

- **Now test the process with DN configuration**
- **Each player picks a type of microbe and places it in suitable conditions in the process**
- **ZONE 1:**
  - Each player picks two wastewater constituent.
  - Try to form suitable sets for your microbe's reaction using influent wastewater and zone conditions.
  - When a reaction occurs, select the correct end-products
  - Check if possible reactions exist with the end-products
- **ZONE 2:**
  - Move the wastewater constituents and the end-products that have not yet reacted to zone 2.
  - Repeat the steps from zone 1.
- **RAS flow**
  - Move the wastewater constituents and the end-products that have not yet reacted to zone 1 via RAS flow.
  - Repeat the steps from above.
- **GAME ENDS WHEN ALL THE REACTIONS HAVE OCCURRED.**

Storage processes

Role of storage processes in growth

- **Substrate can be converted and stored within bacterial cells as energy storage.**
- **Bacterial growth can be based on direct growth on the substrate or on growth on these storage polymers.**
- **Growth on storage has a bit lower yield (energetically less efficient) – 4 - 10% less sludge production.**
- **Common storage polymers Polyhydroxyalkaonate PHA and polyhydroxybutyrate PHB**
- **Storage polymers are a benefit in bacterial competition.**



PHA & PHB

PHA

- Up to 90% cell dry weight
- Similar characteristics to plastics
- Biodegradable
- Example: Mars, Attero Venlo (PHA from biowaste)

PHA&PHB production

Important things to consider

- **Production yield**
- **Volumetric productivity**
- **PHA&PHB concentration**
- **PHA&PHB composition**

PHB: example Mirel (USA)

Caproates: animal feed,

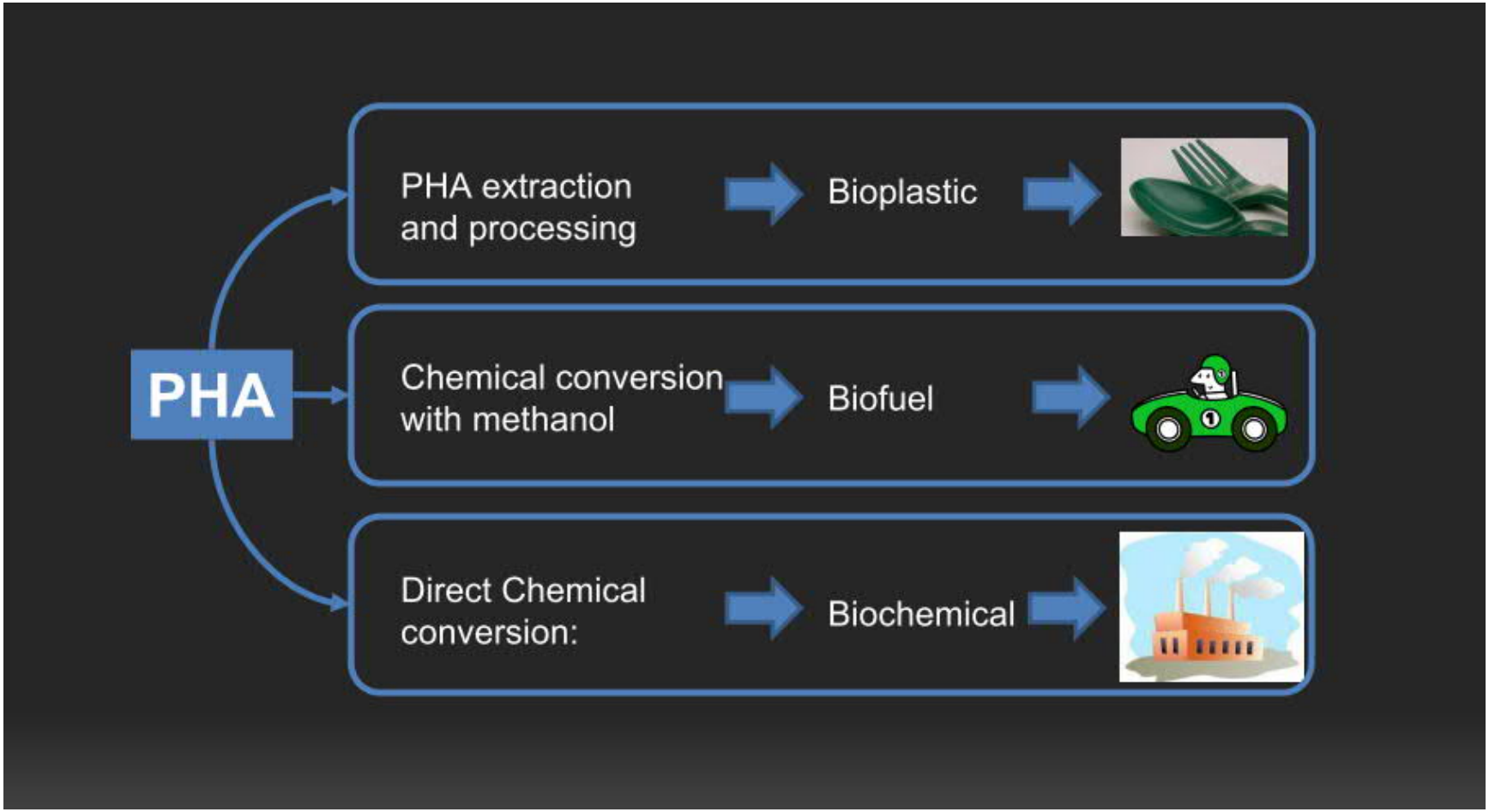

PHA
PHA extraction and processing
Bioplastic
Chemical conversion with methanol
Biofuel
Direct Chemical conversion:
Biochemical

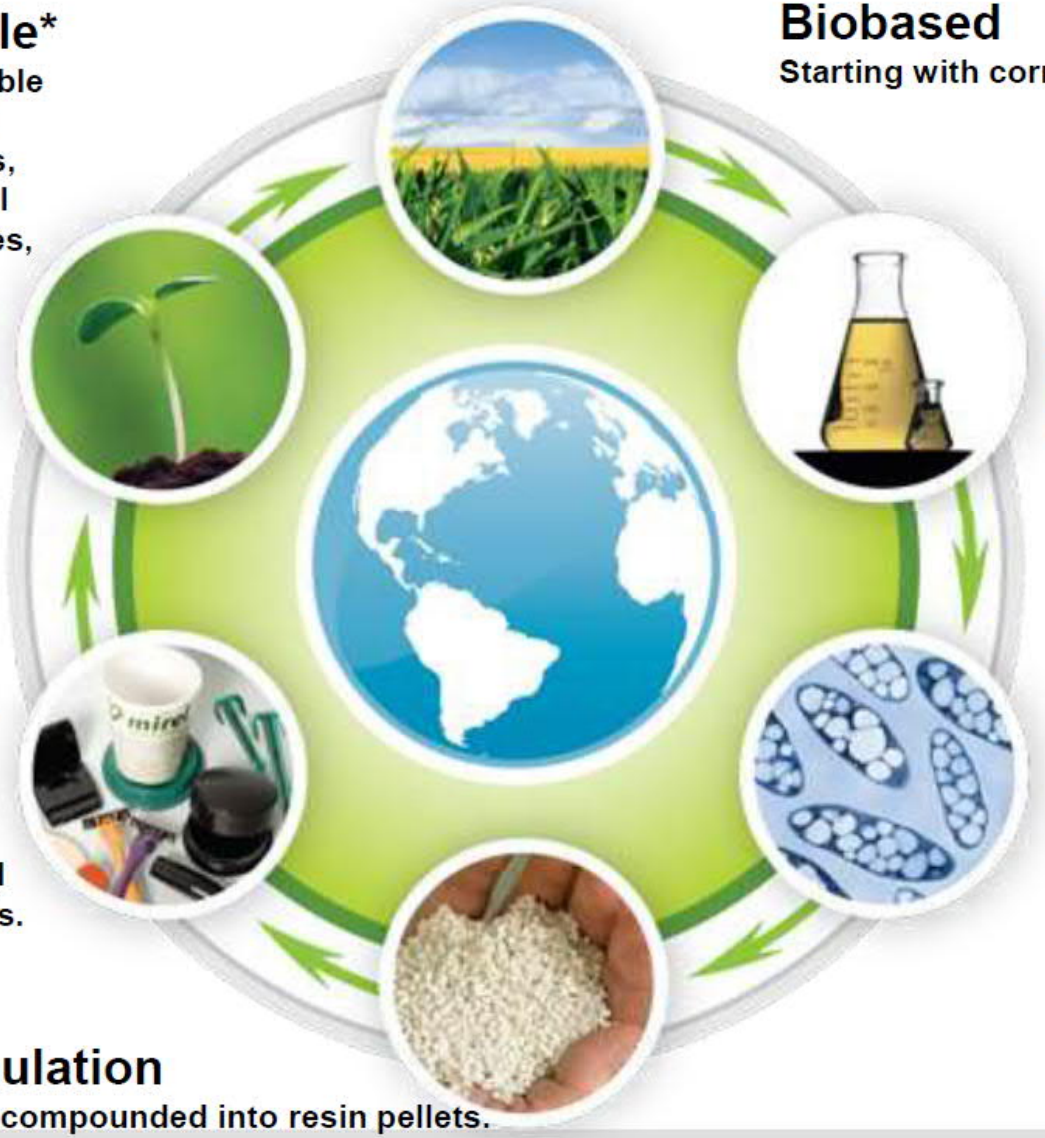
Table 15.1 Some Companies Involved in PHA Production.

Company	Products
Berlin Packaging Corp. (U.S.)	Zeneca/ICI Biopol
Bioscience Ltd. (Finland)	Medical applications of PHAs
Bioventures Alberta, Inc. (Canada)	PHA produced by recombinant *Escherichia coli*
Metabolix, Inc. (U.S.)	PHB, P(HB : HV) (Mirel)
Metabolix/ADM	Transgenic plant PHAs
Monsanto (U.S.)	Transgenic plant PHAs
Polyferm, Inc. (Canada)	PHAs from hemicellulose; use of *Burkholderia cepacia* on xylose
Monsanto-Metabolix (U.S.)	Biopol from *Cupriavidus necator*
Nodax Procter and Gamble (U.S.)	PHBHx, PHBO, PHBOd (Nodax)
Tianan Biologic Material Co (China)	PHB and P(HB : HV) (Enmat)
Tianjin GreenBio Materials Co., Ltd. (GreenBio) (China)	Sogreen
Biocycle Copersucar (Brasil)	PHB and P(HB : HV) (Biocycle)
Biomer (Germany)	PHB and P(HB : HV) (Biomer L)
BIO-ON (Italy)	Minerv-PHA (from sugar beets)
NatureWorks LLC (U.S.)	Ingeo biopolymer
Micromidas	Constructed microbial population able to adapt to a variety of materials, including waste

How Mirel is Made

Biodegradable*
Mirel is biodegradable in natural soil and water environments, home and industrial composting facilities, where available.

Biobased
Starting with corn.



Corn Sugar
One of many products made from each kernel of corn, used as feedstock for Mirel.

Applications
Mirel can be processed on conventional equipment and used in everyday products.

Fermentation
A patented process, transforms the sugar into Mirel biopolymers.

Formulation
Mirel is compounded into resin pellets.

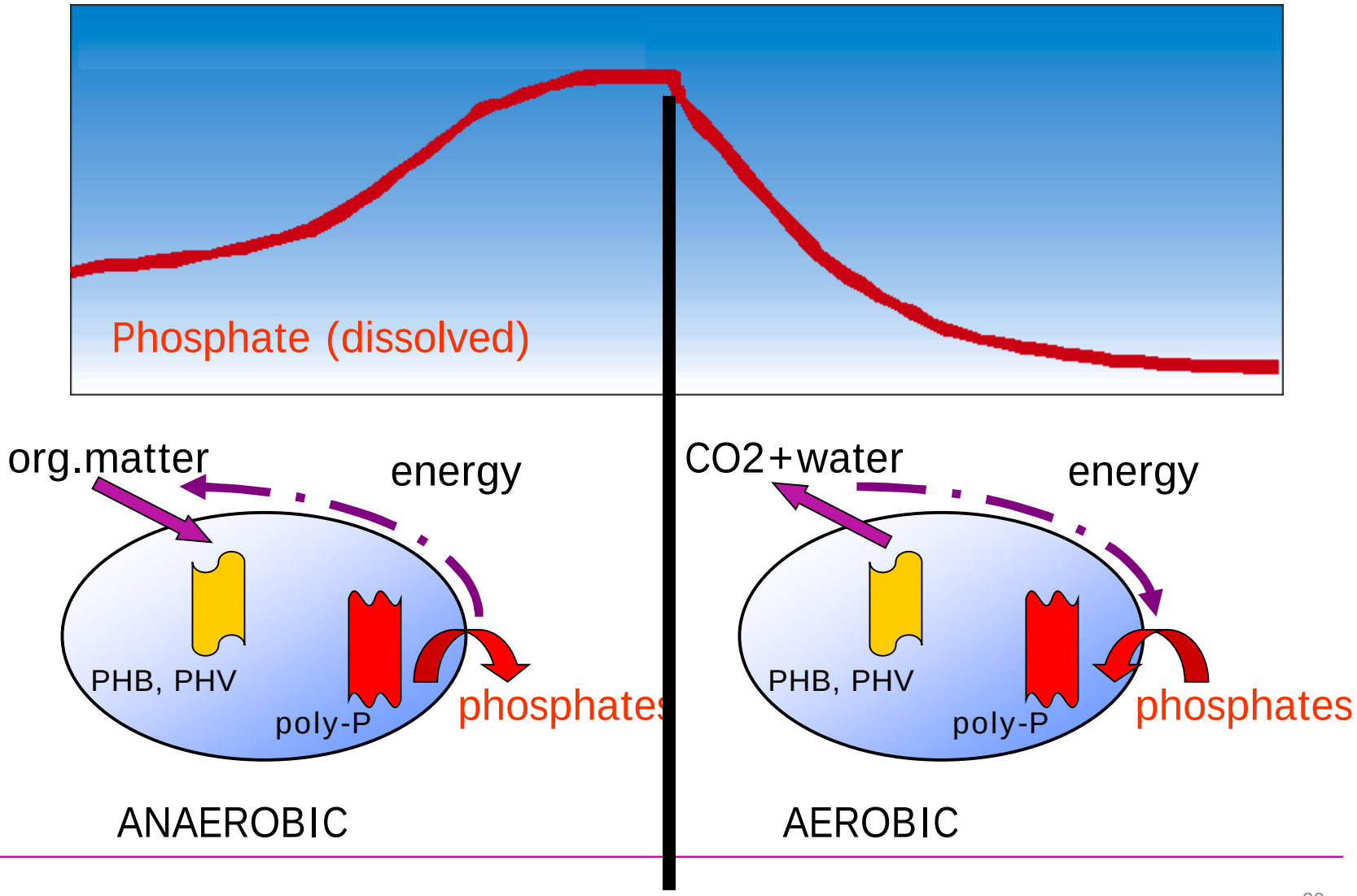
BREAK

Biological phosphorus removal

Biological phosphorus removal

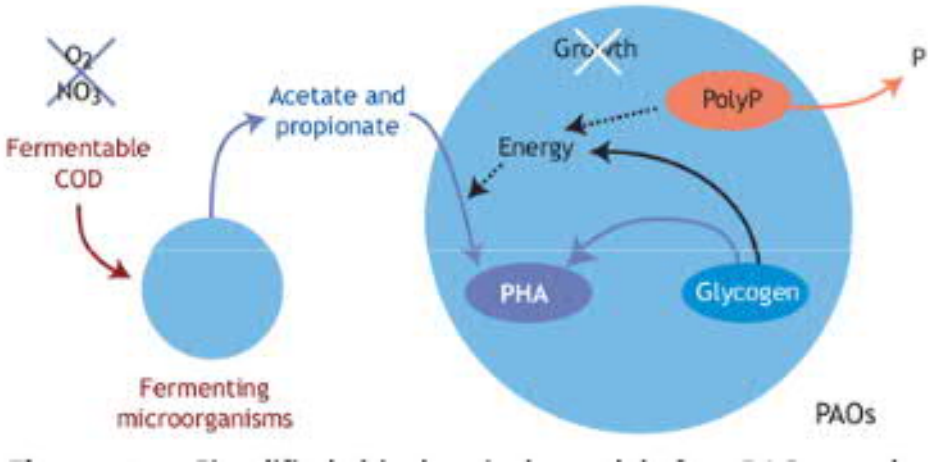
- Phenomenon was discovered by accident in India 1959
- Observed in full-scale plant in South Africa in the 70s also by accident
- Based on microbes capable of storing polyphosphates
- Require alternating anaerobic (not even nitrates) and aerobic conditions and carbon source in the anaerobic phase.
- PAOs phosphorus accumulating organisms
- Competition with GAOs (Glycogen accumulating organisms) especially in warm temperatures

BioP

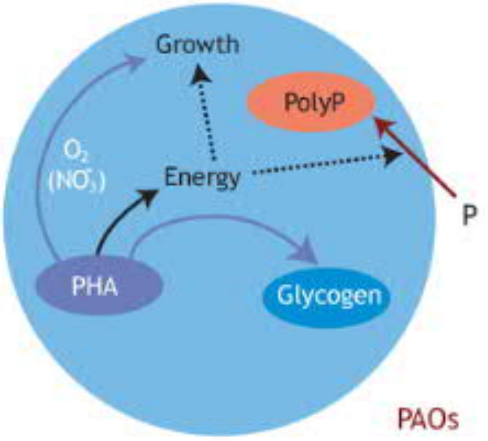

Phosphate (dissolved)
org.matter
energy
PHB, PHV
poly-P
phosphates
ANAEROBIC
CO2+water
energy
PHB, PHV
poly-P
phosphates
AEROBIC

BioP

ANAEROBIC CONDITIONS

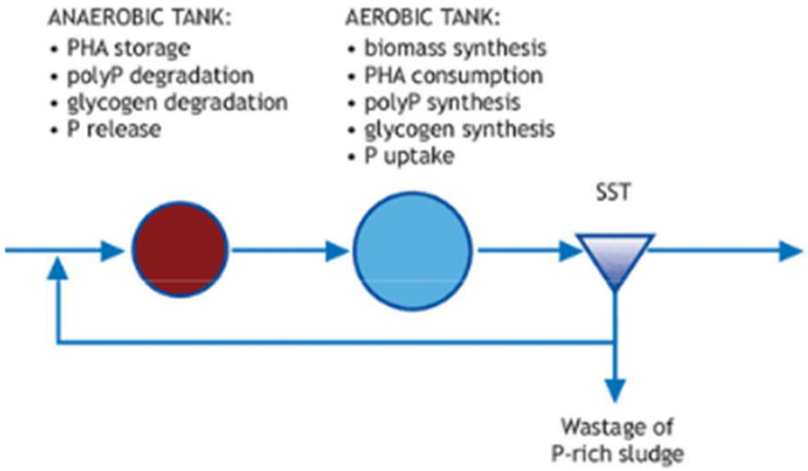


AEROBIC CONDITIONS



Principles of bioP

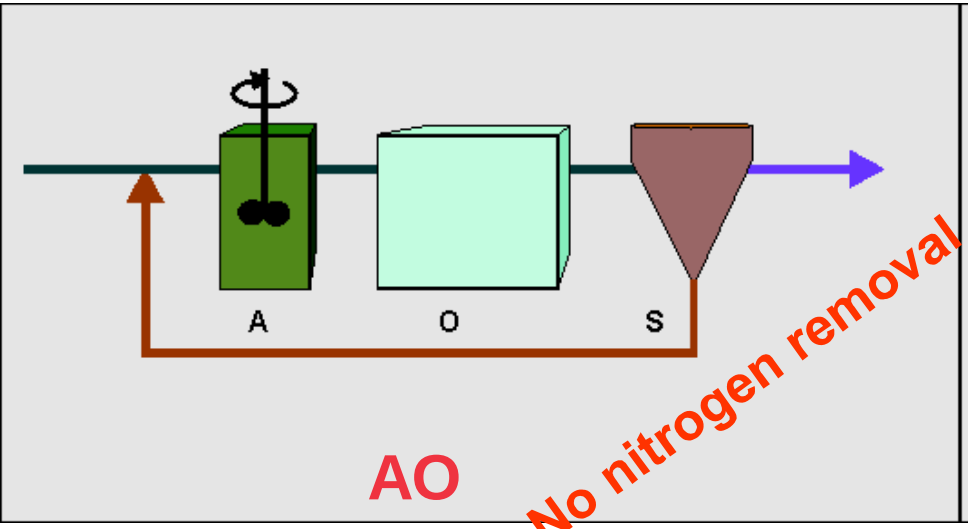
- Phosphorus accumulating organisms (PAOs) store organic matter as polyhydroxyalcanoates (PHA) in anaerobic conditions using energy from poly-P inside the cell
- In aerobic conditions PAOs store more poly-P than needed for the normal metabolism using stored PHA
- Phosphorus is removed with the sludge (3-8 % of P)



Important aspects in bioP processes

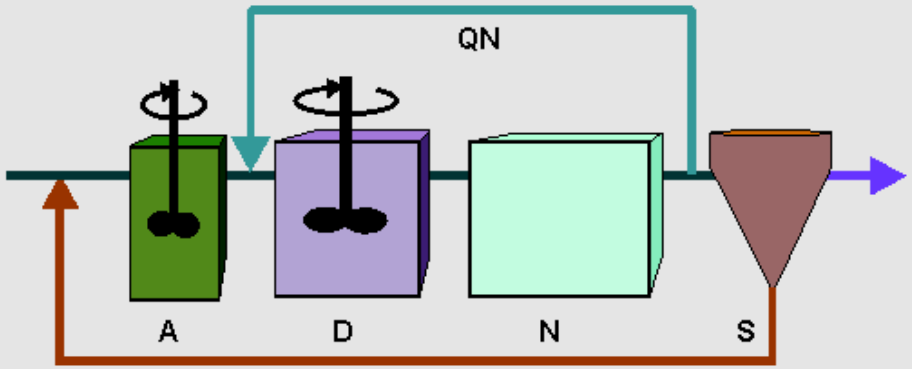
- Minimizing oxygen in the anaerobic zone
- Minimizing nitrates and nitrites in the anaerobic zone.
- Increase volatile fatty acids (VFA) concentration in the anaerobic zone. (VFA is taken up and forms PHA)
- Minimizing solids in the effluent (high P content)
- Maximizing phosphorus uptake = short SRT and good oxygen concentration pattern

Biological P removal processes

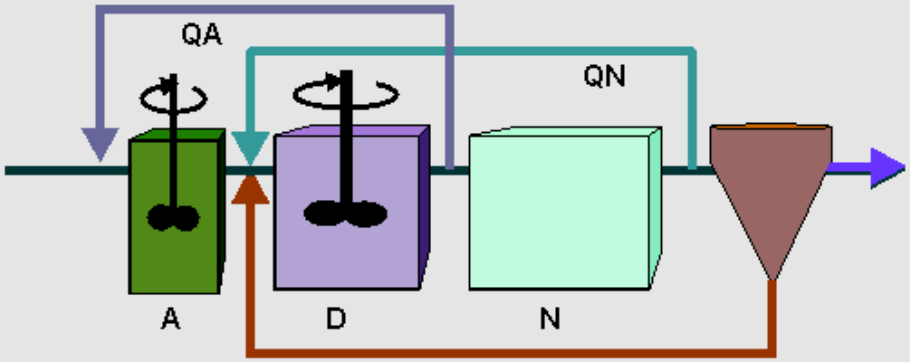


AO

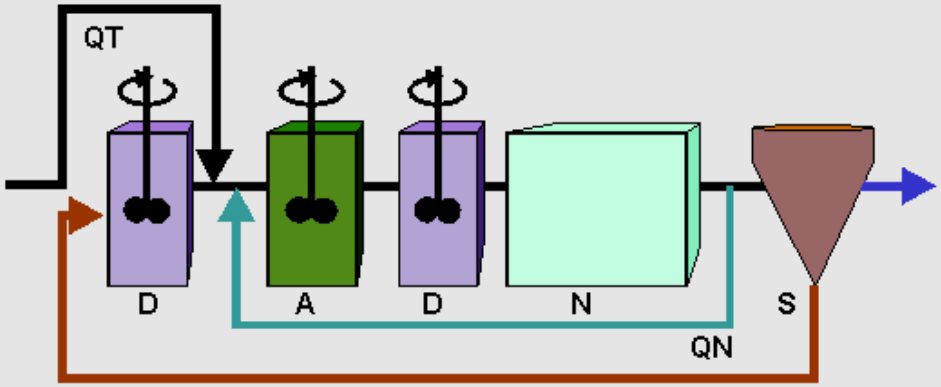
No nitrogen removal



AAO



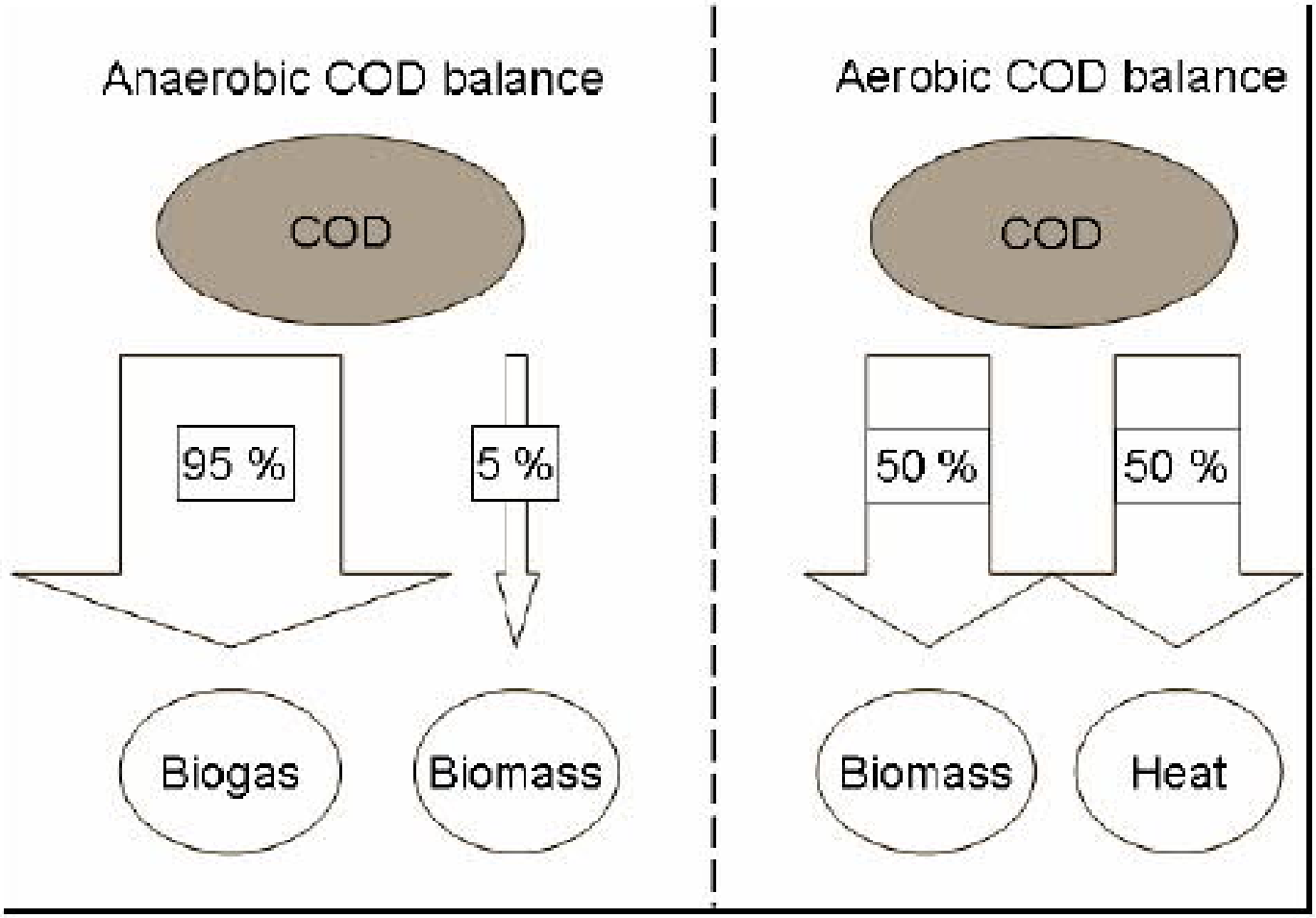
UCT



JHB

Anaerobic processes

Why anaerobic treatment?

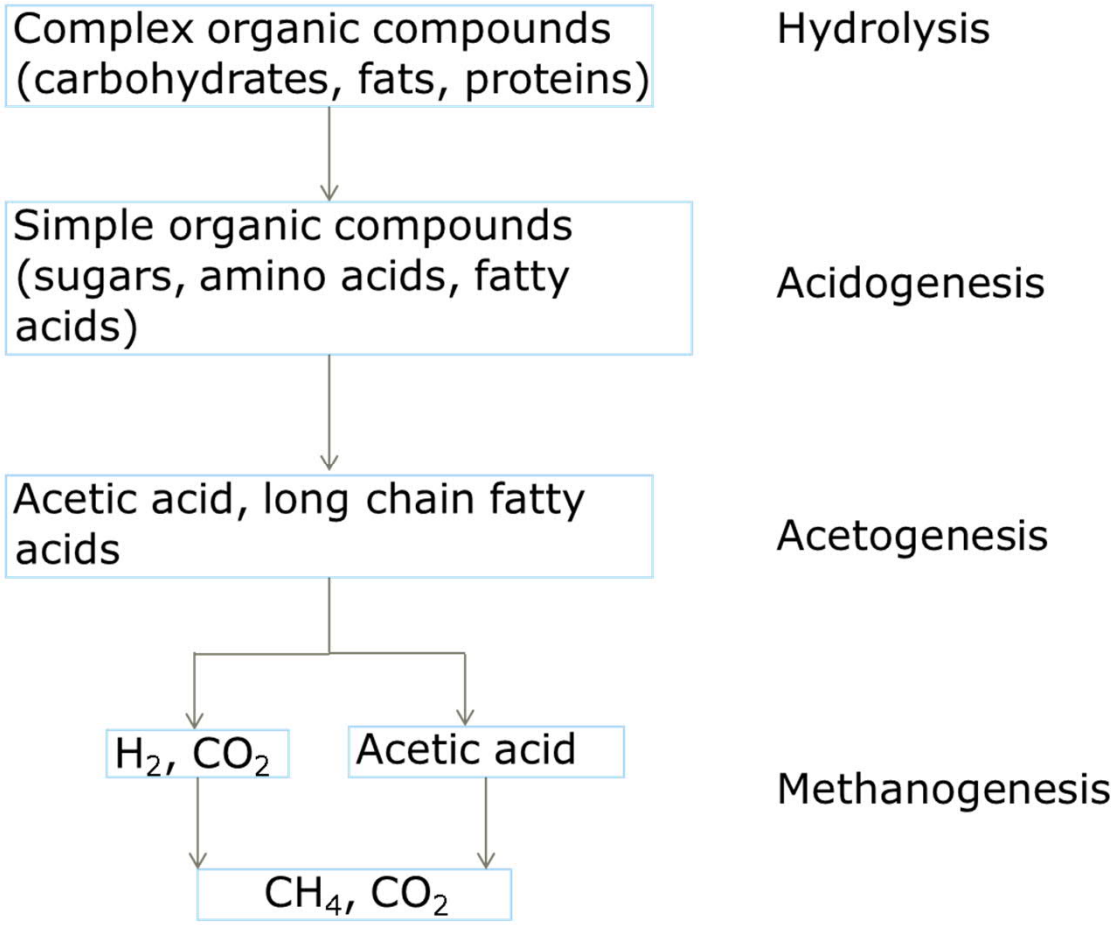


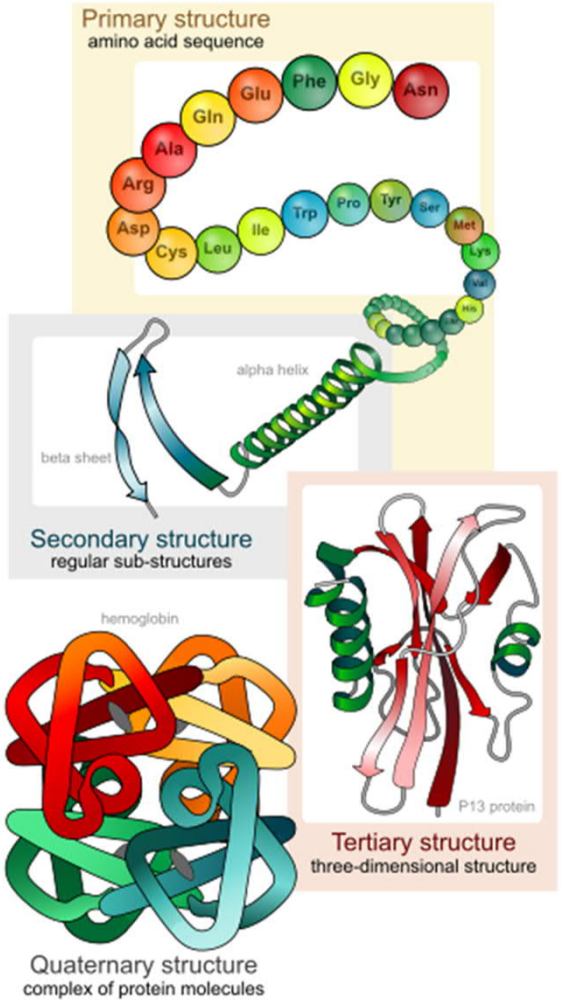
Pros and cons of anaerobic digestion

+ CO_2 as electron acceptor
+ no need for aeration
+ Low sludge yield
+ Produces methane, 90% can be used as energy (9000 kcal/m^3)
+ high loading→ less space
+ Works with certain organic compounds that can not be degraded in aerobic conditions

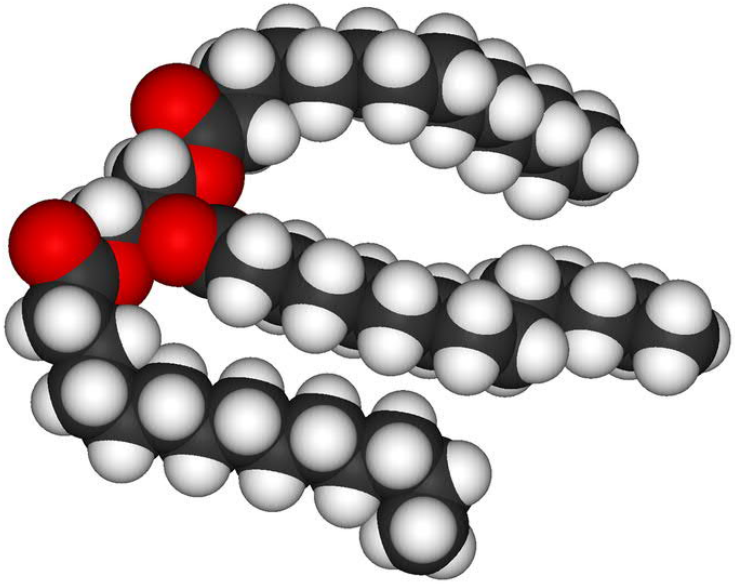
- Slow process (HRT about 30 d)
- Sensitive to toxic substances
- Long start-up
- Requires high substrate concentrations

Anaerobic digestion

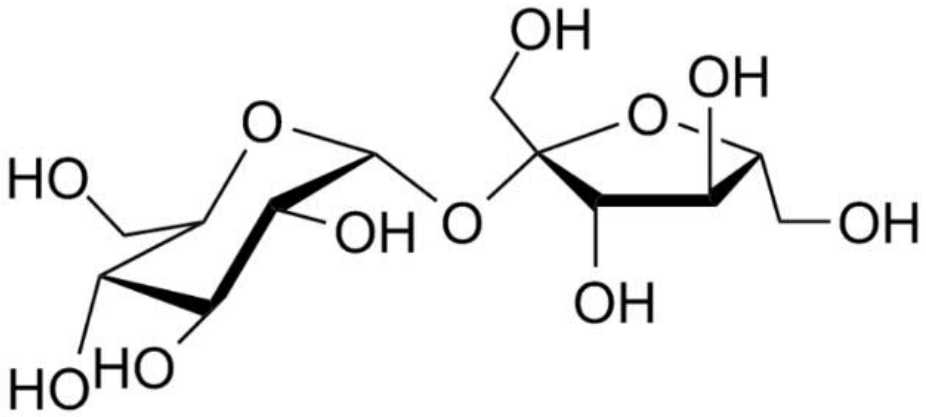




Proteins



Fats (triglyseride molecule)

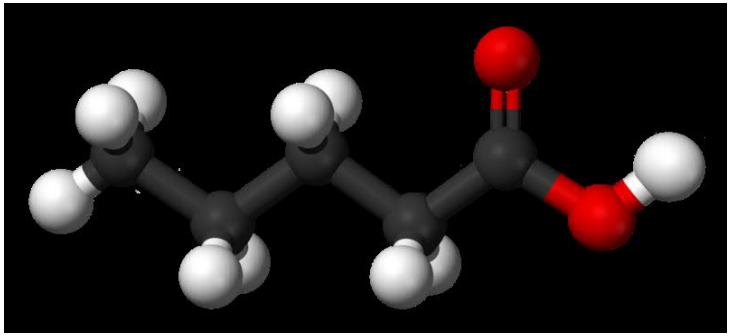


Sugar

Hydrolysis

- First step of the anaerobic digestion
- Different groups of bacteria produce extracellular enzymes to cut the larger organic molecules into smaller ones
- Larger molecules = proteins, fats, carbohydrates
- Smaller molecules = small molecule sugars, amino acids, short chain fatty acids

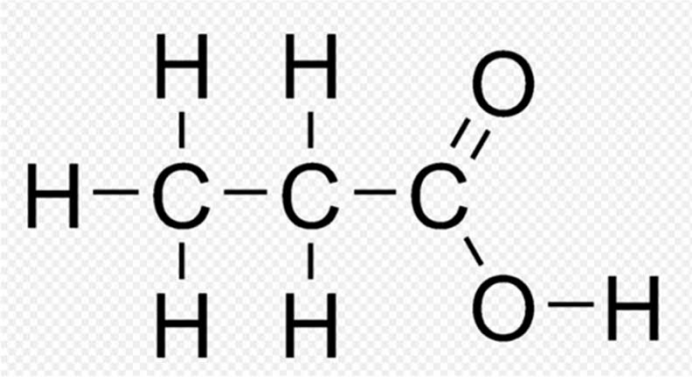
Hydrolysis products, example valeric acid



Acidogenesis

- **Second step of the anaerobic digestion**
- **Acidogenesis**
- **Bacteria degrades the organic molecules further to short-chain fatty acids and alcohols**
- **Ammonium, hydrogen and CO_2 also produced**

End product in this step, for example propanoic acid



Acetogenesis and methanogenesis

- **Third step of the anaerobic digestion**
- **Acetogenic bacteria degrades the short chain fatty acids to acetic acid (and hydrogen and CO_2)**

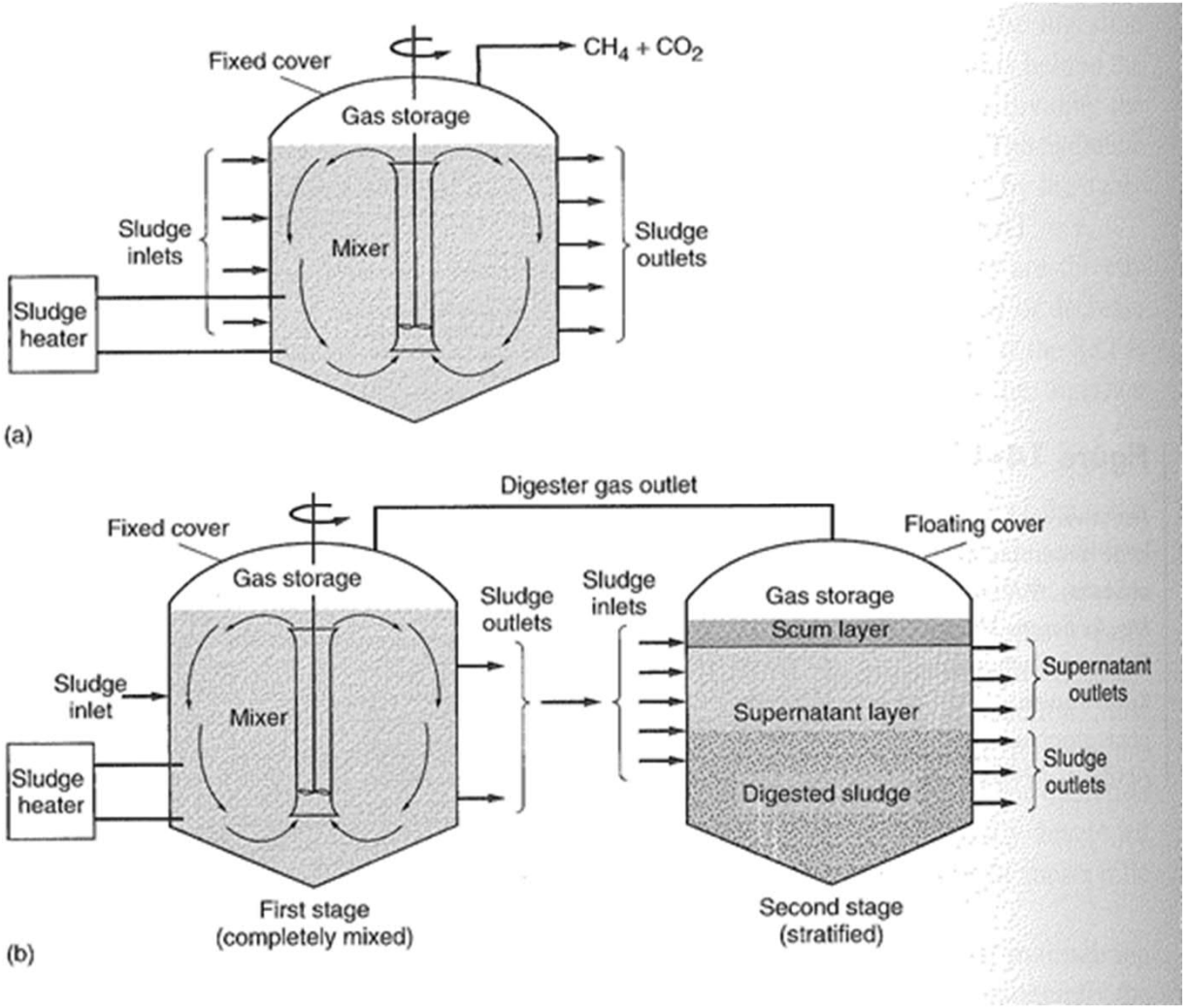
Last step of the anaerobic digestion

Methanogenic bacteria use acetic acid, CO_2 and hydrogen to produce biogas (=methane)

Pre-fermentation

- **In order to produce VFA = volatile fatty acids**
- **VFAs are enhancing denitrification and biological phosphorus removal**
- **Can be done with influent waste water, raw sludge, waste activated sludge or a industrial influent**

Anaerobic processes for sludge digestion (biogas plants)



Digestion processes

Mesophilic

33 – 37 ºC

Retention time about 21 days

Thermophilic

54 – 55 ºC

Retention time about 14 days

Requires more energy

Anaerobic processes in wastewater treatment

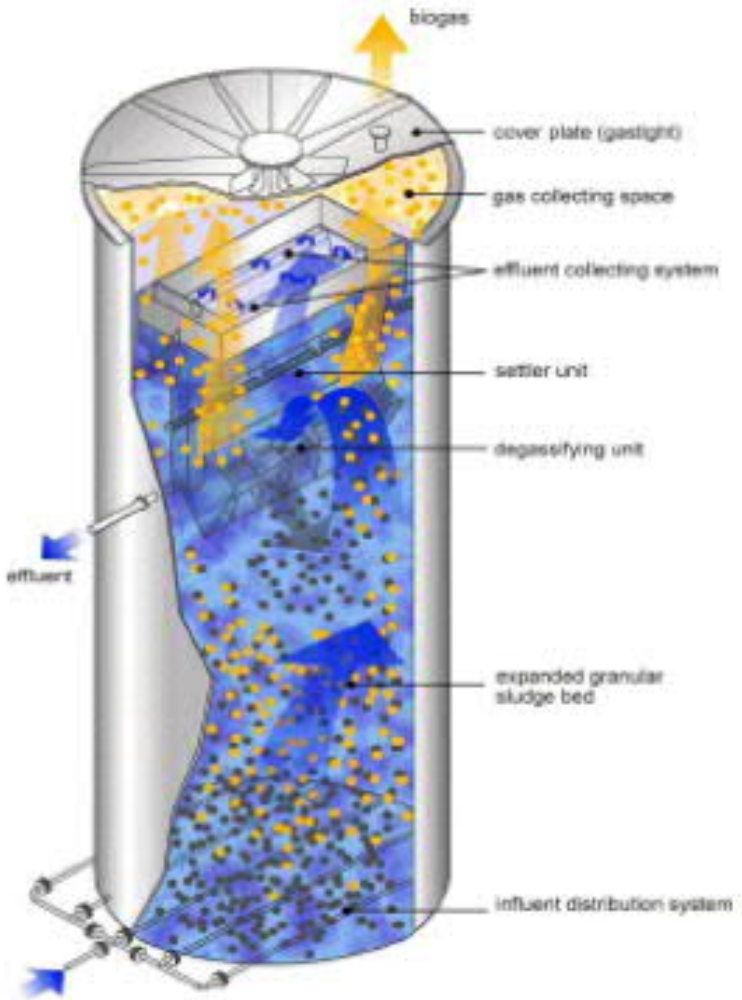


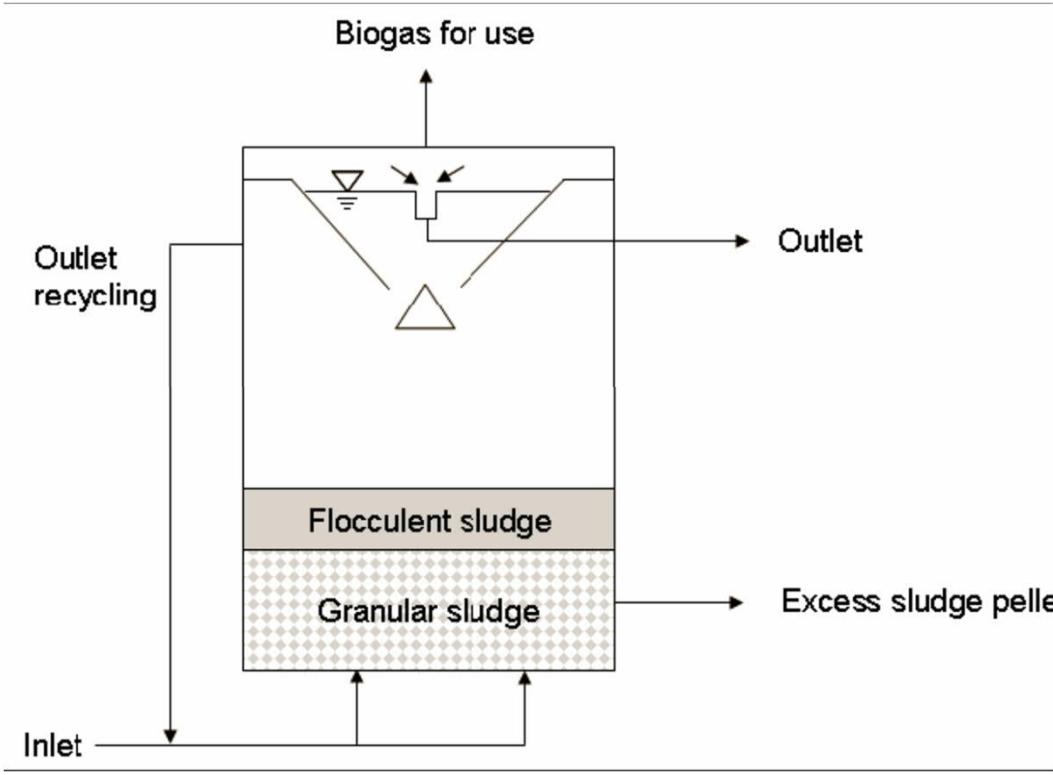
Figure 1: Typical Biobed® EGSB reactor

Typical Biobed® EGSB plant at Lapin Kulta, Haparanda (Finland)

UASB reactor (Upflow anaerobic sludge blanket)

Granular biomass is created in the reactor

Biomass is kept in suspension by the gravity of the granules and the upflow of wastewater



Reading material

Biological wastewater treatment (Course book):

Chapters

2.1

2.2.7 – 2.2.8

2.3

2.4

7.1 – 7.4