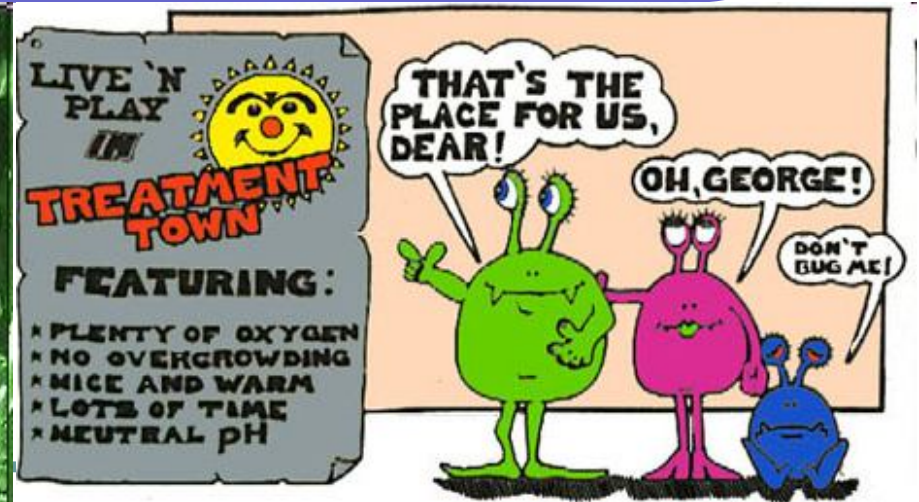
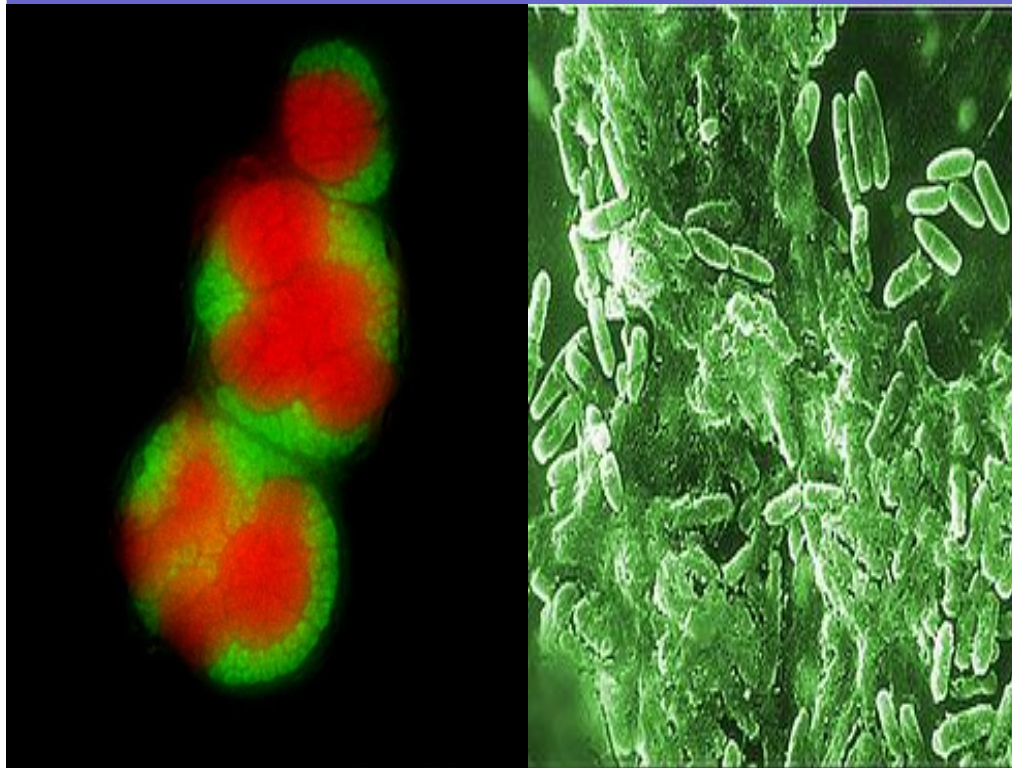


Chapter 3: Principles of Biological Wastewater Treatment & Process Selection



Raúl Muñoz

Pedro Garcia Encina₁

Part I: Carbon removal

TYPE OF MICROORGANISMS

CLASSIFICATION	ENERGY SOURCE	CARBON SOURCE
Heterotrophs		
Chemoheterotrophs	RE-DOX reaction	Organic C
Photoheterotrophs	Light	Organic C
Autotrophs		
Chemoautotrophs	RE-DOX reaction	CO ₂
Photoautotrophs	Light	CO ₂

Aerobic Carbon Removal

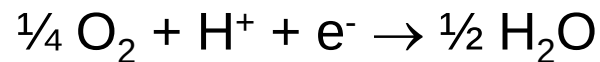
Organics compounds are used as source of carbon and energy (heterotrophic growth):



Organic matter

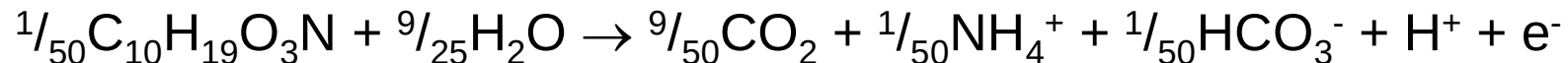
Biomass

Electron acceptor



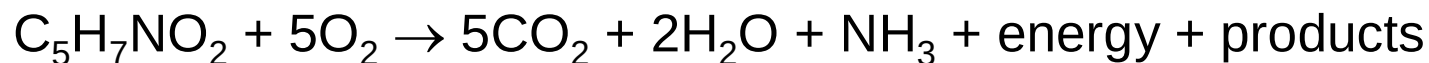
C-source

Energy source: Electron donor



Endogenous Decay

- Endogenous decay accounts for the loss in cell mass due to: A) oxidation of internal storage products for energy for cell maintenance, B) cell death and C) predation by organisms higher in the food chain.
- μ -organisms require energy for cell maintenance in all growth phases; however the decay coefficient most probably changes with cell age. Usually, these factors are lumped together: It is assumed that the decrease in cell mass caused by them is proportional to the concentration of μ -organisms present. The decrease in mass is often identified in the literature as the endogenous decay:



Consequence of endogenous decay:

Less sludge produced / Higher O_2 demand / Increase in effluent COD (by-products) and Nutrients

Anoxic carbon removal

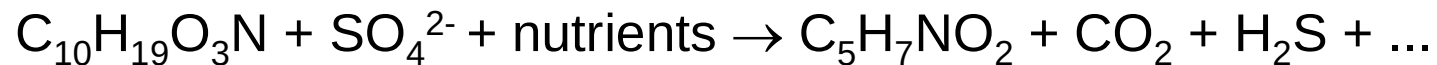
- There are several definitions of what anoxic conditions are. In WWTPs, this often means that O_2 is absent and replaced by nitrate or sulfate as electron acceptor.

Nitrate as electron acceptor



This process is also known as denitrification (N-removal)

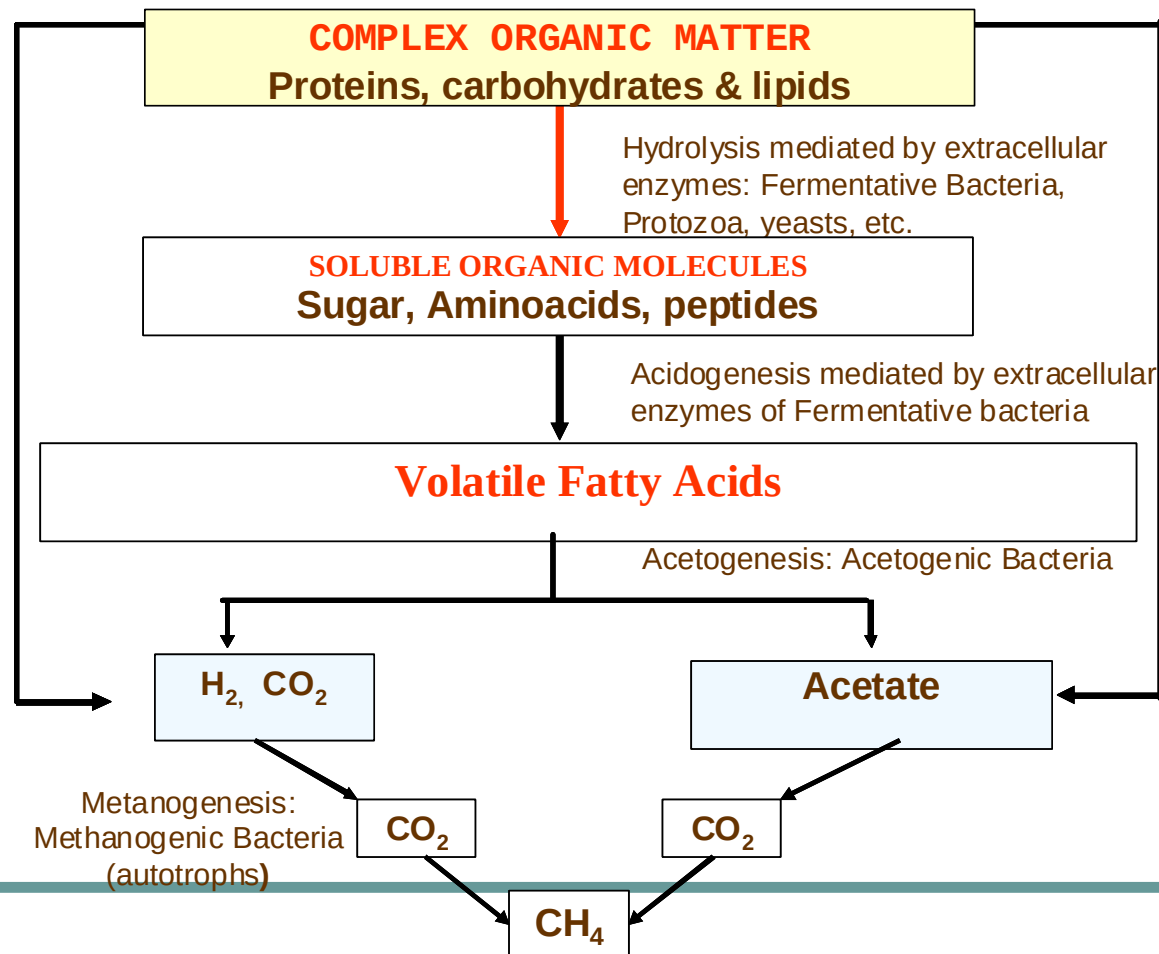
Sulfate as electron acceptor



H_2S formation results in bad smells & corrosion

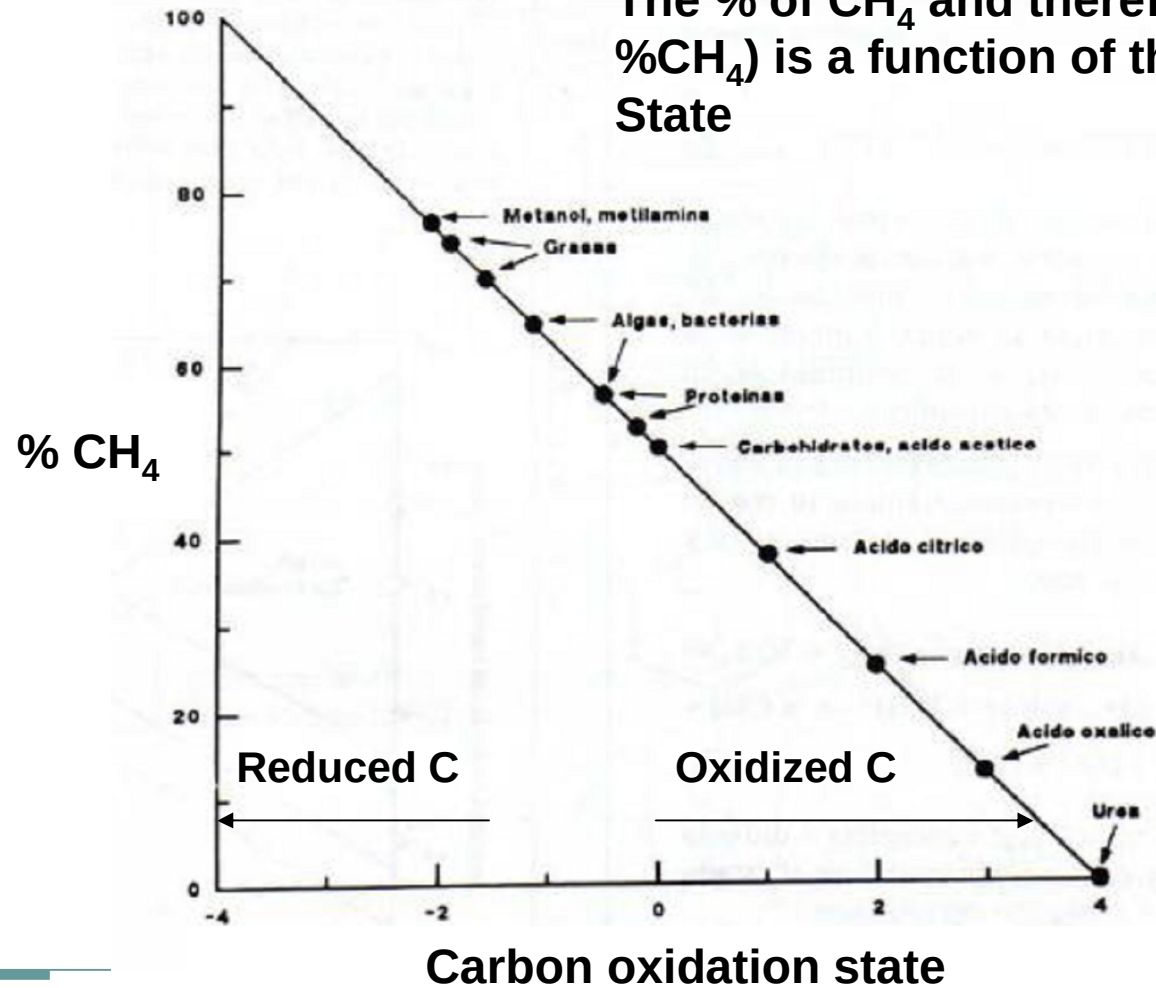
Anaerobic carbon removal

Organic Matter $\rightarrow$ Biomass + CO_2 + CH_4 + NH_3



Biogas Composition

The % of CH_4 and therefore CO_2 ($\approx 100 - \% \text{CH}_4$) is a function of the C oxidation State



(Lema et al. 1992)

Aerobic/Anaerobic/Anoxic

Calculate the amount of energy released from the oxidation of wastewater ($C_{10}H_{19}O_3N$) under aerobic, anoxic and anaerobic conditions:

Electron acceptor:

- $\frac{1}{4} O_2 + H^+ + e^- \rightarrow \frac{1}{2} H_2O$ $\Delta G^0 = -78.14 \text{ kJ/e}^- \text{ eq}^*$
- $\frac{1}{5} NO_3^- + \frac{6}{5} H^+ + e^- \rightarrow \frac{1}{10} N_2 + \frac{3}{5} H_2O$ $\Delta G^0 = -71.67 \text{ kJ/e}^- \text{ eq}$
- $\frac{1}{8} CO_2 + H^+ + e^- \rightarrow \frac{1}{8} CH_4 + \frac{1}{4} H_2O$ $\Delta G^0 = 24.11 \text{ kJ/e}^- \text{ eq}$

Electron donor:

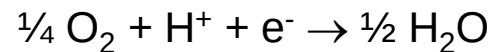
- $\frac{1}{50} C_{10}H_{19}O_3N + \frac{9}{25} H_2O \rightarrow \frac{9}{50} CO_2 + \frac{1}{50} NH_4^+ + \frac{1}{50} HCO_3^- + H^+ + e^-$ $\Delta G^0 = -31.80 \text{ kJ/e}^- \text{ eq}$

Knowing part of the energy released is used for biomass synthesis, what can you expect on the biomass yield under these conditions)

*-Note ΔG^0 = Gibbs free energy under standard conditions (pH 7, 25 °C). If necessary, the real ΔG must be calculated taking into account activities and non-standard conditions.

Solution

Aerobic



$$\Delta G^0 = -78.14 \text{ kJ/e}^- \text{ eq}$$



$$\Delta G^0 = -31.80 \text{ kJ/e}^- \text{ eq}$$

$$\Delta G = -109.94 \text{ kJ/e}^- \text{ eq}$$

Anoxic: $\Delta G = -103.47 \text{ kJ/e}^- \text{ eq}$

Anaerobic: $\Delta G = -7.69 \text{ kJ/e}^- \text{ eq}$

There is no straight correlation between the amount of energy released and the energy available for cell synthesis. However, it is clear that more energy is available for cell synthesis under aerobic and anoxic conditions $\Rightarrow \mathbf{Y_{aer} \cong Y_{anox} \gg Y_{ana}}$

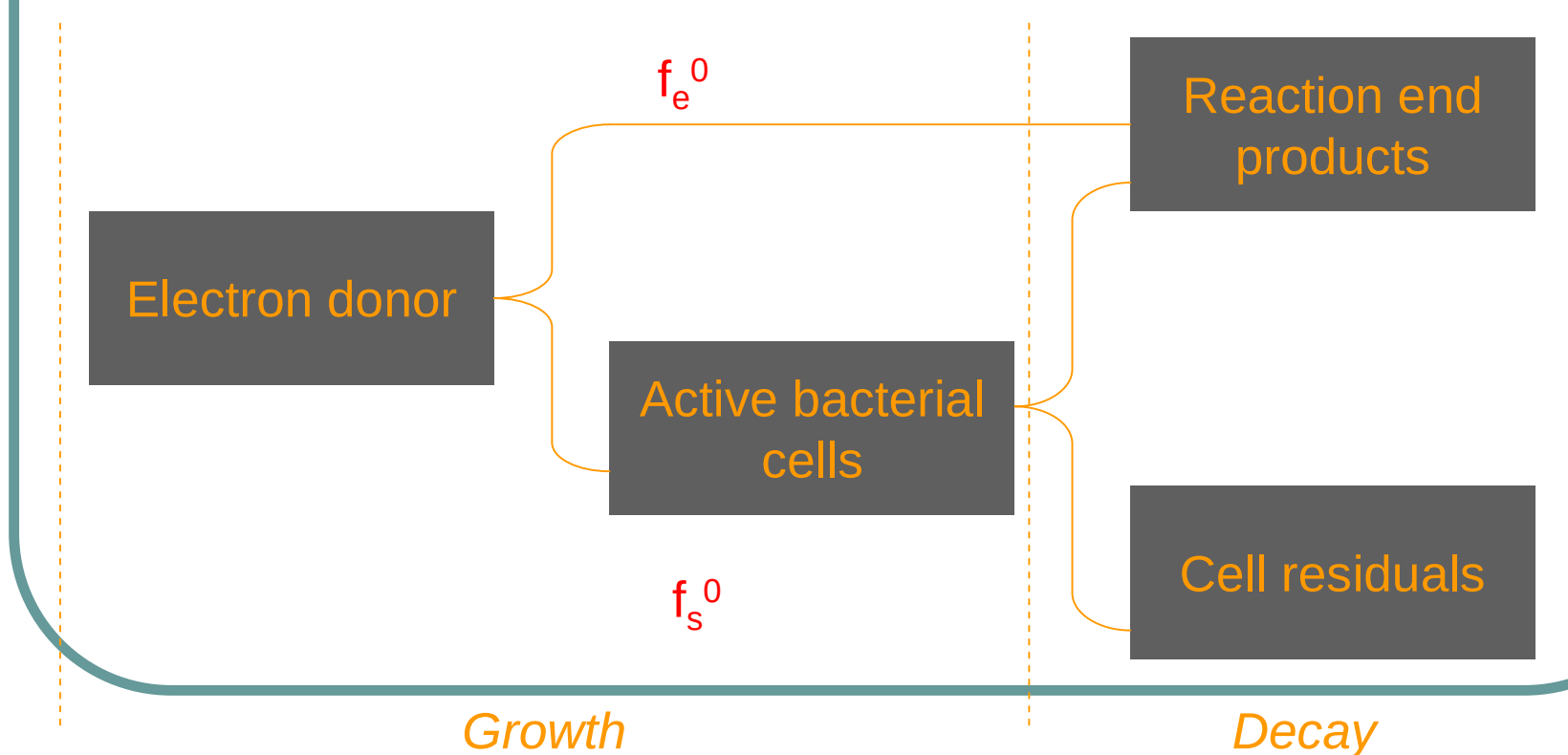
where Y = true biomass yield $\text{g VSS}_{\text{formed}}/\text{g COD}_{\text{used}}$

Typical values: $Y_{\text{aer}} = 0.4$, $Y_{\text{anox}} = 0.3$ and $Y_{\text{ana}} = 0.06 \text{ g VSS/g COD}$

Consequences: Anaerobic processes leads to much less sludge (and heat) production. Less nutrients will be consumed under anaerobic treatment.

Microbial energetics

- When microorganisms use an electron-donor substrate for synthesis, a portion of its electrons (f_e^0) is initially transferred to the electron-acceptor to provide energy for conversion of the other portion of electrons (f_s^0) into microbial cells. $f_e^0 + f_s^0 = 1$



True Yield and Net Yield

- The fraction f_s^0 can be converted into mass units (i.e. g cell produced/g COD used) and is therefore another expression of the true yield Y .
- The true biomass yield Y , is defined as the amount of biomass produced (in g or C-mol) per amount of substrate (electron donor) used (in g, C-mol or g COD).
- However, the net yield is lower than the true yield because of decay.
- The fraction f_e and f_s are used for the net yield:
 $f_e > f_s^0$; $f_s < f_s^0$ and $f_e + f_s = 1$

Effect of load/substrate concentration

- If the substrate supply is growth-limiting, a higher proportion of the energy from the e-source is consumed for maintenance, representing the energy that microorganisms must spend for non-growth associated cell survival metabolism. Less energy is therefore available for growth.
- Typically, for aerobic degradation:
 - a) Saturating substrate supply (high loading rate conditions, e.g. $> 0.6 \text{ kg BOD m}^{-3} \text{ d}^{-1}$):
 $1 \text{ g organic-C} \rightarrow 0.5 \text{ g C-CO}_2 + 0.5 \text{ C-cell}$
 - b) Limiting substrate supply (low loading rate conditions):
 $1 \text{ g organic-C} \rightarrow 0.7 \text{ C-CO}_2 + 0.3 \text{ C-cell}$
- Typically, for anaerobic degradation:
 $1 \text{ g organic-C} \rightarrow 0.95 \text{ C-(CO}_2\text{+CH}_4\text{)} + 0.05 \text{ C-cell.}$

Heterotrophic Growth Theory

- During Chemoheterotrophic growth, microorganisms use an organic compound as both energy and carbon source.
- What the μ -organisms really want is to grow, meaning converting the organic compound into biomass. However, this synthesis requires energy and this energy is generated from the organic compound oxidation using an electron acceptor.
- In conclusion, a portion of the organic substrate must be spent to obtain energy and is not available for cell synthesis. The portion depends on many parameters but especially bioenergetics.

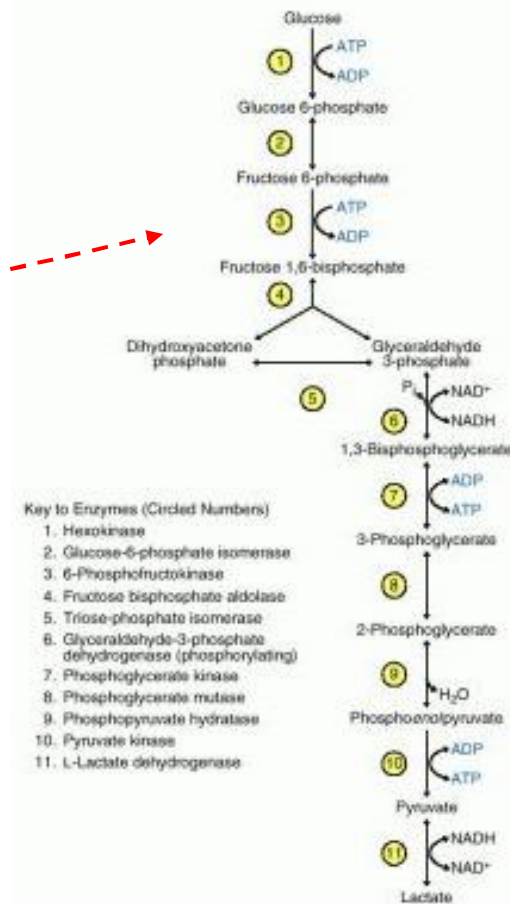
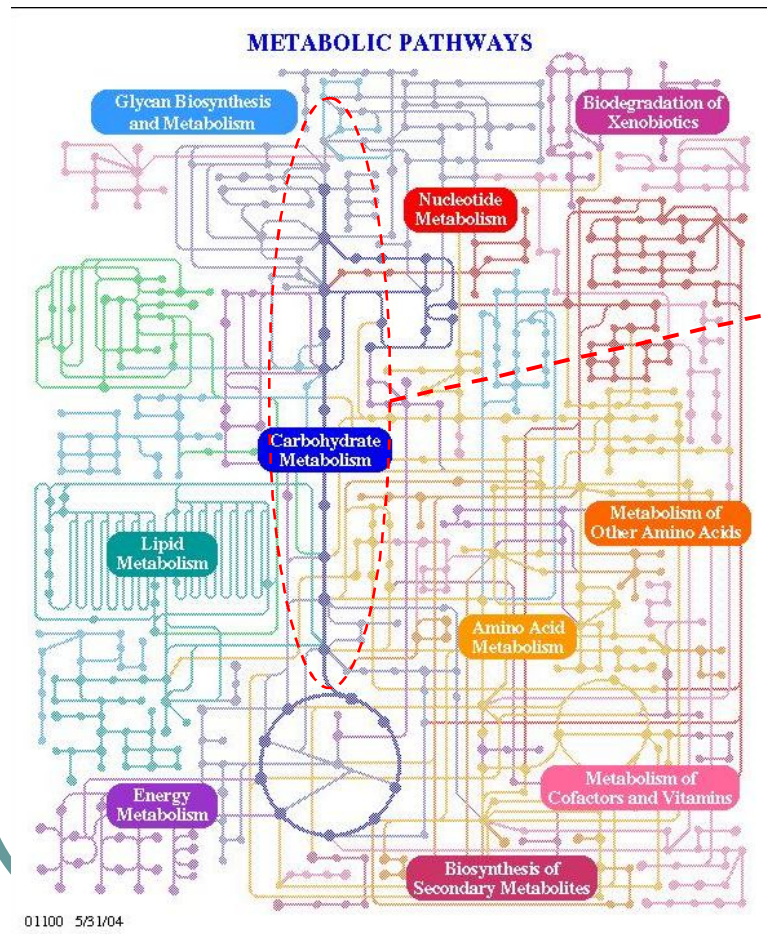
Overall Reaction for Biological Growth

- The overall reaction can be summarized in 2 basic equations: 1 for **Energy Production (Re)** and 1 for **Biomass Synthesis (Rs)**.
- **Re = Ra - Rd**; where Ra is the half-reaction of the electron acceptor reduction (i.e. $\frac{1}{4}\text{O}_2 + \text{e}^- + \text{H}^+ \rightarrow \frac{1}{2}\text{H}_2\text{O}$) and (-Rd)* is the half-reaction of the electron donor oxidation. *Re is the reaction of the e-donor oxidation.*
- **Rs = Rc - Rd**; where Rc represents the half reaction of CO₂ reduction into biomass and (-Rd) is, as described above, the electron donor oxidation into CO₂. *Rs is the reaction of C-source conversion into biomass.*
- **Obviously, the reality is far more complex and involve many steps (which impacts energy efficiency and kinetics) but from a simple energy-thermodynamic point of view, it is acceptable to make such assumptions.**

* By convention, half equations are typically given as $\text{Ox} + \text{e}^- \rightarrow \text{Rd}$. Be careful of siggs!

Metabolic Pathway

Huge amount of reactions in a 10 μm confined space



Overall Reaction for Biological growth

There is a conservation of the amount of electrons in the system.

Thus $R = f_e R_e + f_s R_s$

Where R represents the overall equation of electron donor conversion into cells and oxidation products (mol e⁻-eq/s).

$$R = f_e(R_a - R_d) + f_s(R_c - R_d)$$

where $f_e + f_s = 1$

Thus, $R = f_e R_a + f_s R_c - R_d$



The electron donor is oxidized and generates electrons and CO₂ which are used for *Energy Production* and *Biomass Synthesis*



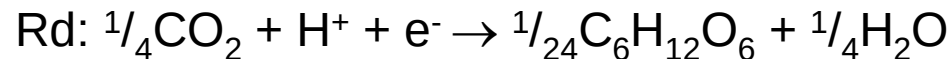
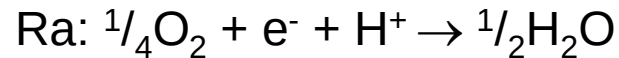
Energy production
(e⁻ are needed)



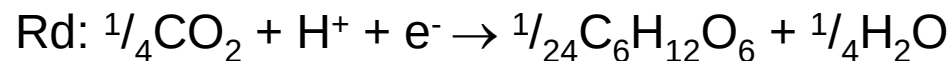
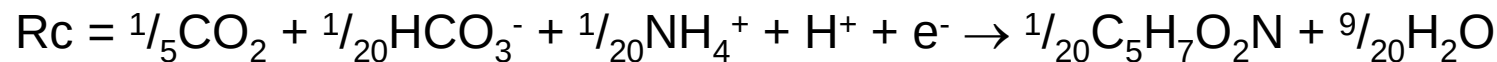
Biomass Synthesis
(CO₂ and e⁻ are needed)

Example: Aerobic oxidation of glucose

Energy Yielding Reaction: $R_e = R_a - R_d$

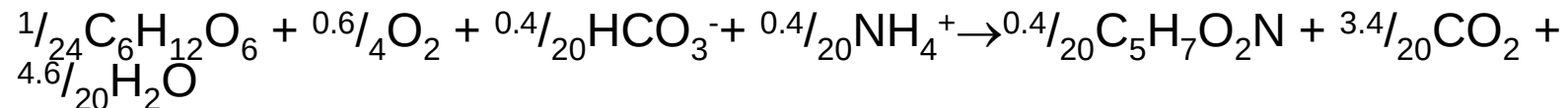


Biomass Synthesis Reaction: $R_s = R_c - R_d$



If we suppose $f_e = 0.6$ and $f_s = 0.4$:

$R = f_e R_a + f_s R_c - R_d = 0.6 R_a + 0.4 R_c - R_d$:



The ThBOD is $(0.6/4) \times 32 / (180/24) = 0.64$ g/g (equivalent to f_e)

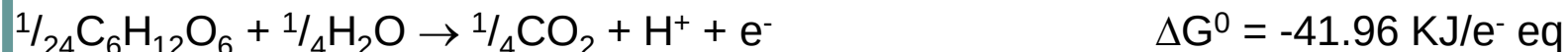
The biomass yield is: $(0.4/20) \times 113 / (180/24) = 0.3$ g/g (equivalent to f_s)

Half -reactions

Conventionally, half reactions are given from the reduction side:



However, it is sometimes more convenient (especially for the electron donor) to write them in the oxidation side. Just be careful of the sign of ΔG^0 ! For instance:



To write down $\frac{1}{2}$ reactions:

Identify the oxidant-reductor couple (i.e. CO_2 /organic, O_2 / H_2O , NH_3 / NO_3^- , NO_3^- / N_2)

Equilibrate C with CO_2 , N with NH_4^+ (and other elements such as Cl with Cl^-)

Equilibrate O with H_2O

Equilibrate H with H^+

Equilibrate the charge with e^- and rewrite the equation per mole of e^-

Equations are typically balanced using $\text{CO}_2 \rightarrow \text{HCO}_3^- + \text{H}^+$ to yield an equal number of H^+ and e^- .

Calculating f_e^0 and f_s^0 from ΔG_0

- The amount of energy released from $f_e^0 \text{Re} = f_e^0 \Delta G_R$ can be easily calculated from the ΔG_0 of the half reactions Ra and Rd.
- We now suppose that **only a fraction of that energy is used to carry out Biomass Synthesis** (fsRs) such as

$$K f_e^0 \Delta G_R = - f_s^0 \Delta G_S \text{ or } K(f_e^0 / f_s^0) \Delta G_R = - \Delta G_S$$

- Where K is the energy efficiency: This “represents” the portion of the energy that is used for cell growth and 1-K is wasted as heat.

ΔG_s

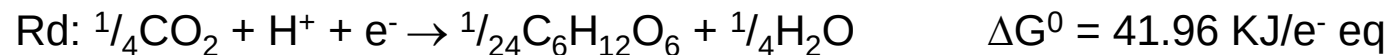
- We assume here that the organic substrate is converted to pyruvate, a cell precursor, and that then pyruvate is converted into cell materials.
- The free energy ΔG_s to convert 1 electron equivalent (e^- eq) of the carbon source into cell material can be calculated as:
- $\Delta G_s = \Delta G_p / (K^m) + \Delta G_c + \Delta G_n / K$
 - ΔG_p = free energy to convert 1 e^- eq of the carbon source into pyruvate with $m = +1$ is $\Delta G_p > 0$ and $m = -1$ if $\Delta G_p < 0$
 - ΔG_c = free energy to convert 1 e^- eq of pyruvate into cell material = 31.41 KJ/ e^- eq
 - ΔG_n = free energy to reduce nitrogen to ammonia, but if ammonia is the nitrogen source, $\Delta G_n = 0$.

Note: Formula and values taken from Metcalf and Eddy. Rittmand and Mc Carty have a slightly different method for calculating ΔG_s

<http://www.wiley.com/legacy/college/boyer/0470003790/animations/tca/tca.htm>

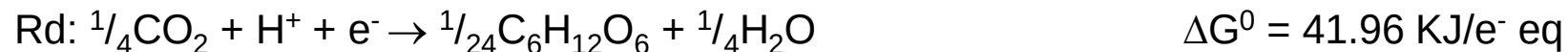
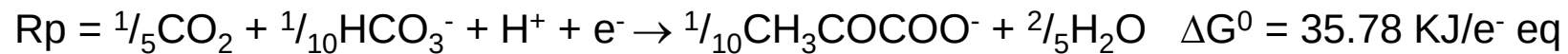
Example: Aerobic degradation of glucose, $K=0.6$

- ΔG_e



- $\Delta G_s = \Delta G_p/K^m + \Delta G_c + \Delta G_n/K = \Delta G_p/K^m + 31.41$

ΔG_p ?



$\Delta G_p = -6.18 \text{ KJ/e}^- \text{ eq}$

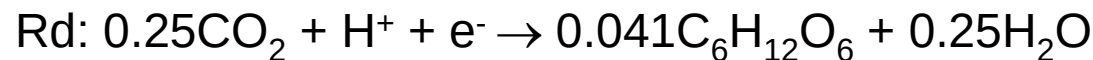
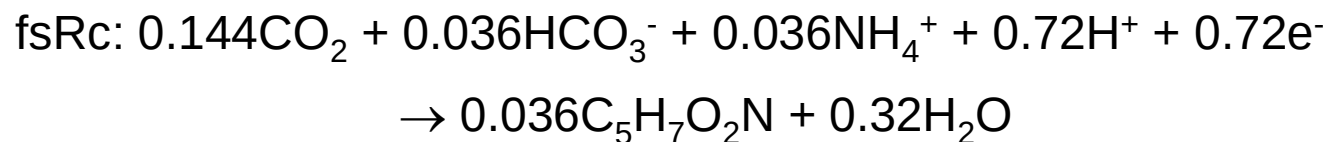
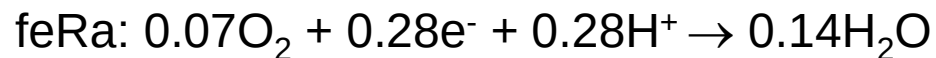
$\Delta G_s = -6.18/0.6^{-1} + 31.41 = 27.7 \text{ KJ/e}^- \text{ eq}$

Example - continued

$$K(f_e^0/f_s^0)\Delta G_R = -\Delta G_S \Rightarrow f_e^0/f_s^0 = -\Delta G_S/(K\Delta G_R) = 0.38$$

$$f_e^0 + f_s^0 = 1 \Rightarrow f_s^0 = 1/(1+0.384) = 0.72 \text{ and } f_e^0 = 0.28$$

$$\blacksquare R = f_e^0 R_a + f_s^0 R_c - R_d$$



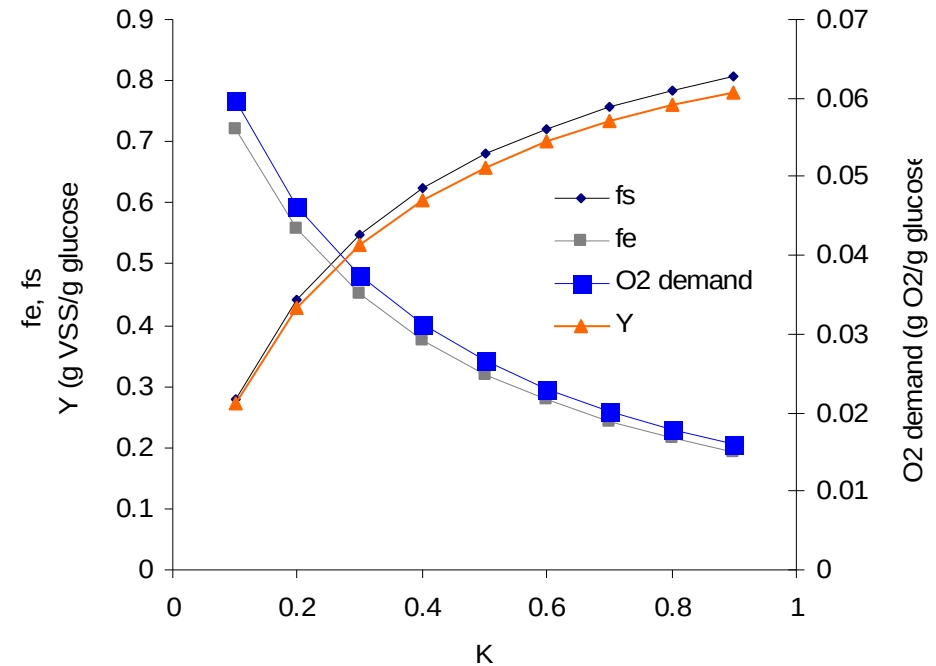
$$\text{C: } 6 \times 0.041 + 0.036 - 5 \times 0.036 - 0.106 = 0$$

$$\text{H: } 12 \times 0.041 + 0.036 + 0.036 \times 4 - 0.036 \times 7 - 0.21 \times 2 = 0$$

$$\text{O: } 6 \times 0.041 + 2 \times 0.07 + 3 \times 0.036 - 2 \times 0.036 - 2 \times 0.106 - 0.21 = 0$$

Consequences

- The lower the efficiency (K), the lower the biomass yield (the lower f_s) and the higher the electron acceptor demand (the higher the f_e)



- This shows biomass yield and electron acceptor (i.e. O_2) demand are inversely proportional.
- In other words, the electron acceptor demand can be easily accessed from the biomass production.

Influence of carbon source and electron acceptor of biomass yield (f_s^0)

- All f_s^0 values in the table shown below were calculated with $K = 0.6$ and NH_4^+ as N source
- Glucose oxidation yields more energy than acetate.

E-donor E-Acceptor	f_s^0 Acetate	f_s^0 Glucose
Oxygen	0.59	0.72
Nitrate	0.57	0.71
Sulfate	0.08	0.31
CO_2	0.05	0.28

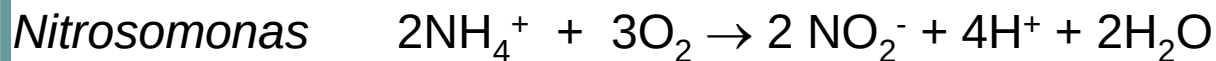
Part II: Nutrient Removal

N-removal

- N-removal from Wastewater is based on the conversion of organic-N and inorganic-N (NH_4^+ , NO_3^- , NO_2^-) into N_2 (that reaches the atmosphere).
- Part of the N is also eliminated via assimilation into biomass

Conventional N-removal involves a 2-steps: nitrification/denitrification processes

Nitrification (Chemoautotrophic Process)



Alkalinity is
required

Denitrification: Electron Donor + $\text{NO}_3^- \rightarrow \text{Biomass} + \text{N}_2 + \text{CO}_2$

7.14 g alkalinity (as CaCO_3)/ g NH_4^+ required!!

Denitrification requires an electron donor: Influent BOD, endogeneous respiration, external C source

N-removal

Organic-N is degraded by heterotrophs (hydrolysis) and usually released as NH_4^+ → The process is called Ammonification

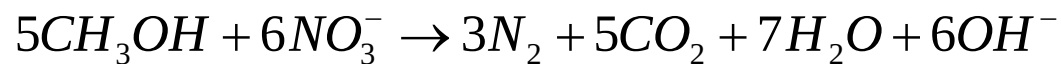
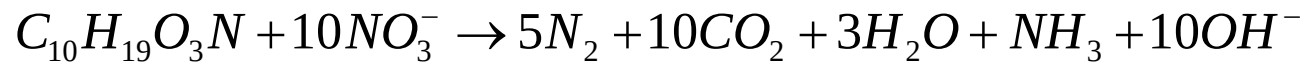
Nitrification is slow and easily inhibited if proper conditions are not met (i.e. presence heavy metals). It is often not seen in BOD_5 tests.

Impact of nitrification during aerobic treatment of BOD:

- Increased O_2 demand
- Increased sludge production (less significant)

N-removal

Denitrification requires an electron donor, it is therefore often combined with C-removal.



3.57 g alkalinity (as $CaCO_3$) / (g NO_3^- reduced) is produced!!

From a COD balance

$$[bsCOD]_{used} = [bsCOD]_{cell\ synthesis} + [bsCOD]_{oxidized}$$

$$[bsCOD]_{used} = 1.42Y_n [bsCOD]_{used} + [bsCOD]_{oxidized}$$

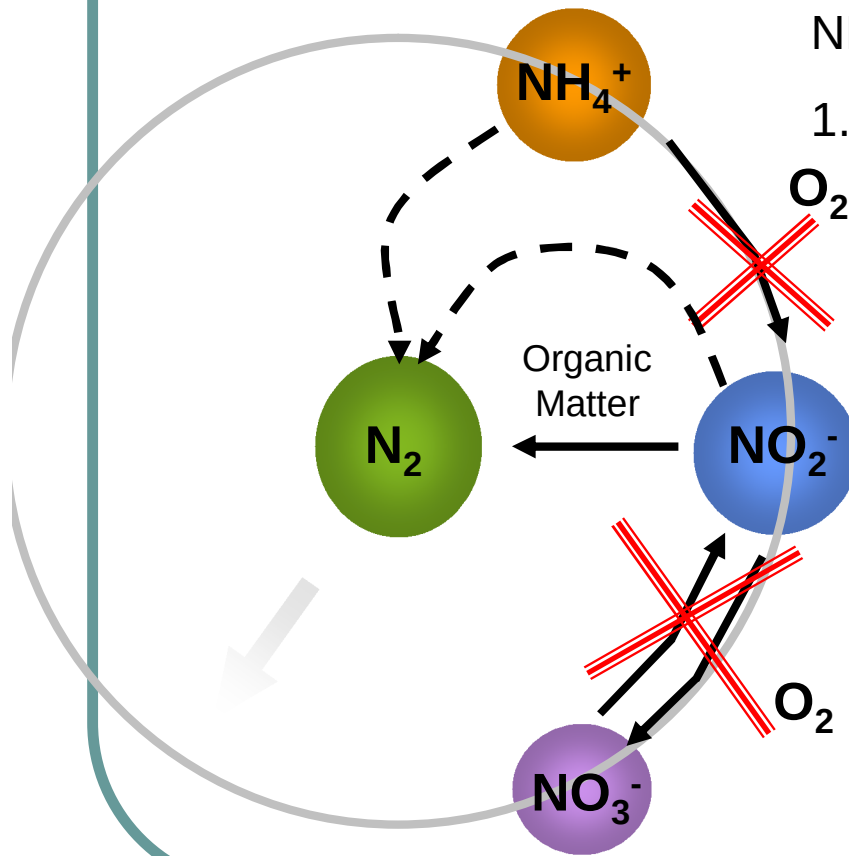
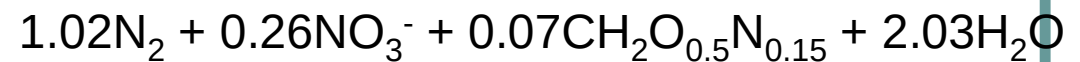
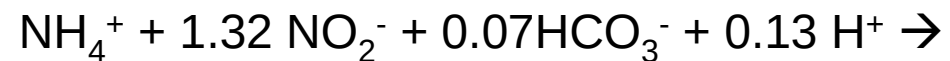
and taking into account that 1 g of $bsCOD_{oxidized}$ = 2.86 g of N - NO_3^-

$$\frac{bsCOD_{used}}{N - NO_3^-} = \frac{2.86}{1 - 1.42Y_n}, \text{ where } Y_n \text{ is the net biomass yield} = \frac{Y}{1 + k_d SRT}$$

1.42 g bsCOD /g VSS

N-removal

Anammox: Anaerobic Ammonia Oxidation



Where NO_2^- is produced in the SHARON process under controlled conditions (partial nitrification under O_2 limiting conditions and 30°C)



Suitable in effluents with a low C/N ratio

Huge energy savings!! Less O₂ required!!!!

P-removal

Biological Phosphorus Removal (BPR) is based upon the special properties of certain heterotrophic bacteria, the **P**hosphorus **A**ccumulating **O**rganisms (**PAOs**), to accumulate polyphosphates as energy reserve under aerobic conditions. A two stage process

Anaerobic process

Acetate is released as fermentation product of COD.

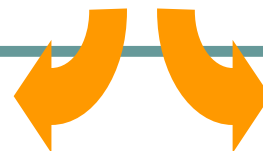
PAOs assimilate acetate into polyhydroxybutyrate (PHB) using the energy accumulated in the form of P-energy bounds, and P is released from internal polyphosphate hydrolysis

As a consequence, PO_4^{2-} is released to the extracellular medium.



Aerobic process

The stored PHB is metabolized as energy and C-source: new cell mass is formed. Polyphosphate is stored in the cells



Excess biomass removed causing phosphate removal

C/N/P removal

Assuming a biomass composition of $C_5H_7NO_2$ (M_w 113 g/mol) and a biomass yield of 0.4 g DW/g COD for aerobic process and 0.06 g DW/g COD for anaerobic process, calculate the amount of nitrogen required for degrading 1 g of COD under each condition.

Solution: 0.05 g N under aerobic and 0.0074 g under anaerobic

Rule of thumb: the COD:N:P ratio (g COD/g N/g P) should be approx. 100:5:1 under aerobic conditions and 250:5:1 under anaerobic conditions (this is of course for bCOD).

This is of course highly dependent on the biomass composition and the process parameters (sludge age, F/M ratio).

Application to WWT

A wastewater from a paper pulp industry has been characterized:

bCOD	2435 mg/l
NH ₄ -N	58 mg/l
PO ₄ -P	1.2 mg/l
NO ₃ -N	35 mg/l
NO ₂ -N	0.26 mg/l

- Which treatment seems more appropriate? (Use rules of thumb)
- Are nutrients needed? How much?
- What happens if an intense endogenous respiration occurs (leading to the decay of approx. 50% of the biomass produced)?
- The effluent guidelines are 10 mg COD/l, 5 mg/l N and 1 mg/l P.

Solution

$$\text{Tot-N} = 58 + 35 + 0.26 = 93.26 \text{ mg N/l}$$

With simplifications:

$$\text{COD:N:P ratio} = 2435 : 93.3 : 1.2$$

$$\text{COD:N:P} = 100:3.8:0.05 = 250 : 9.6 : 0.12$$

These ratios allows you to quickly see what is the compound that is in excess in regards to the “rule of thumbs” ratios. **Note that now, COD represents the carbon available in the organic matter!**

Excess of COD (C) under aerobic conditions, and an excess of N under anaerobic conditions. A logical selection would be a classical aerobic removal process. Under aerobic conditions, for each g of COD consumed 0.05 and 0.01 mg of N and P will be assimilated in the biomass. To consume 2435 mg/l COD, you will then need 121.75 mg N and 24.35 mg/l of P. You will need to add 28.5 mg/l N (36.6 mg NH_4^+) and 23.13 mg/l P.

Anaerobic treatment

If carbon-removal was performed anaerobically, $2435 \times 5/250 = 48.7$ mg/l of nitrogen will be removed by assimilation into biomass, meaning 45.6 mg will remain, which is above the 5 mg/l guidelines. Biomass formation will consume 9.74 mg of P (need for addition of P). The process must be completed with nitrification/denitrification.

Alternatively, 2228 mg COD/l can be added using a free “organic matter” source (i.e. industrial wastewater), and the process can be operated as anaerobic C-removal.

Anaerobic treatment of “low strength” effluents is actually not recommended due to the low biomass yield (meaning not enough biomass can be produced to maintain a high biological activity).

Endogenous respiration

Basically, if 50% of the biomass produced from the COD consumption is degraded, the overall biomass yield decreases by half. This also means twice as less N and P can be assimilated and removed with the biomass (in reality, N and P are assimilated, but are then released during biomass decay).

The new COD:N:P ratio should then be 100:2.5:0.5 for aerobic treatment and 250:2.5:0.5 for anaerobic treatment.

In case of aerobic treatment, you will now have an excess of N and P of 32.4 (need of 60.9 mg/l) but still a deficiency of P (need 12.1 mg/l). You will not be able to meet the N guidelines anymore!

This illustrates a common problem as reduction of sludge production (by lowering the biomass yield) means less nutrients can be removed by assimilation. Similarly, sludge digestion generates the release of N and P which are normally re-introduced into the waste stream (15-20 % of the waste streams). This might offset the C:N:P balance.

Removal of Pathogens

Removal of pathogens can be achieved/improved by

Heat

pH increase

High Oxygen Concentration

This can be achieved in “for free” in algal-ponds and compost

Algal ponds: algal synthesis

Sun light $\Rightarrow$ heating effect

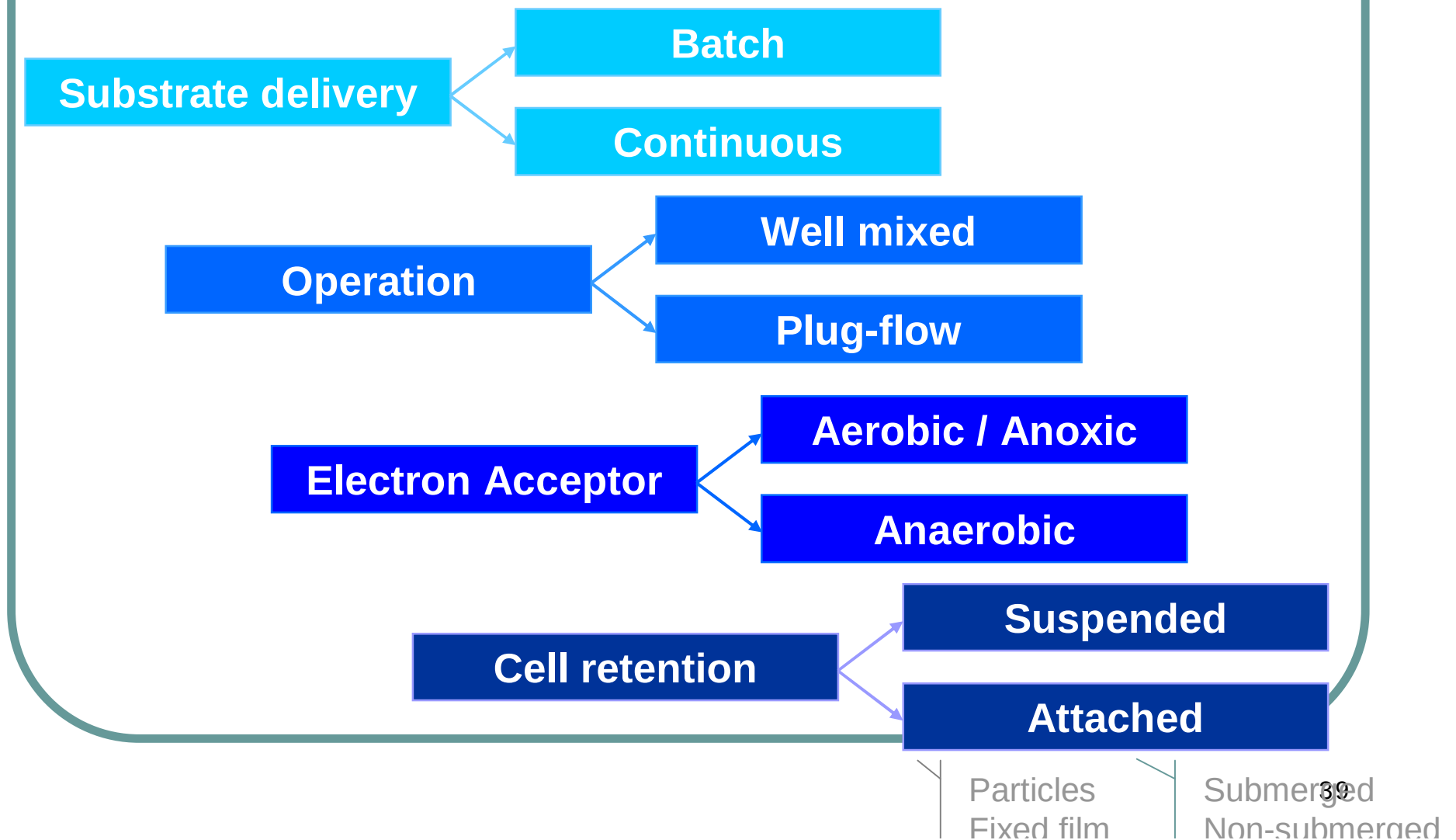
CO₂ consumption $\Rightarrow$ pH increase

[O₂] production $\Rightarrow$ toxic to pathogens

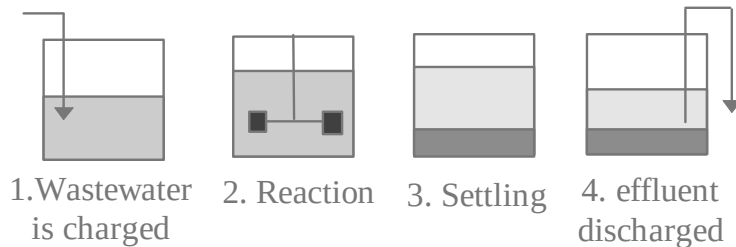
Composting: Use of thermophilic microorganisms

Part III: Introduction to Process selection

Classification of Bioreactors & Biological processes



Sequential Batch/ Batch/ Continuous



Batch & Sequential Batch Reactor (SBR):

Easier control of effluent properties and process performance. The tank is also used as the clarifier

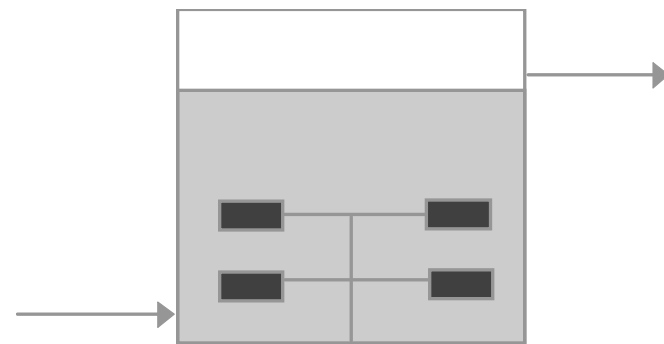
Example of application: Nutrient removal from sludge digester effluent

Continuous:

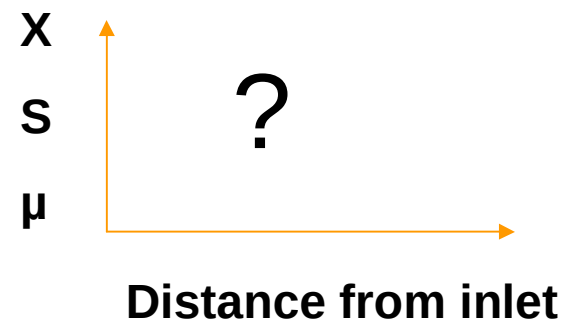
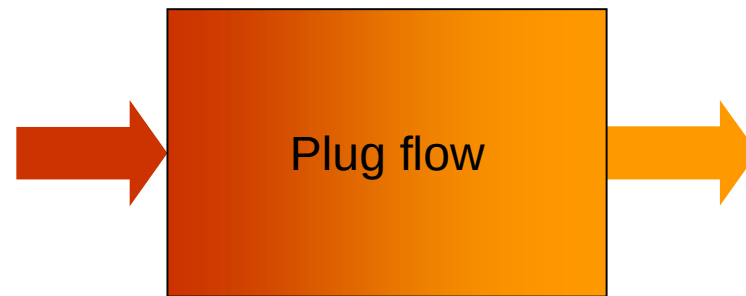
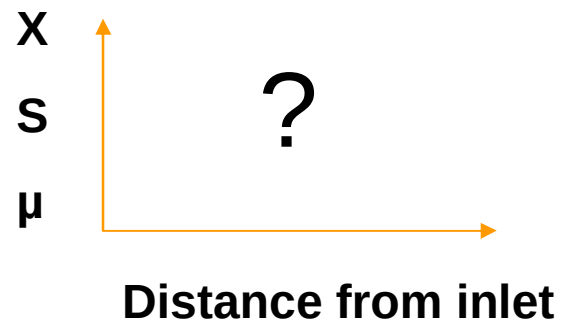
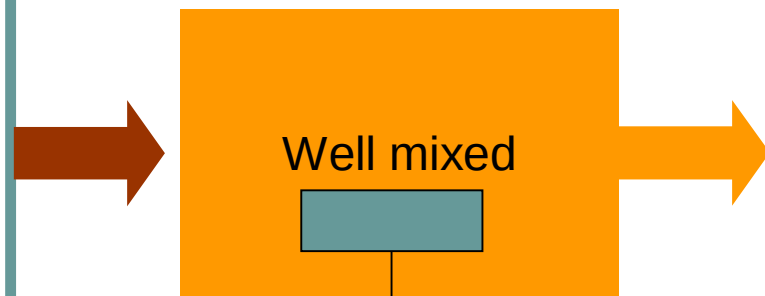
No need for water storage

Suitable for large-scale applications

More sensitive to cell wash out!



Well mixed/ Plug flow



Well mixed/Plug flow

The HRT/SRT in well-mixed and plug flow are practically very similar. For nitrification, the kinetic benefit of the plug-flow can be appreciable.

Well mixed reactors are recommended when oxygen supply is difficult (high oxygen requirement).

Well mixed systems are also recommended when toxic substances can inhibit microbial activity

Plug flow systems are recommended when there is risk of bulking.

Aerobic/anaerobic

Aerobic

- + High biomass productivity allows to design smaller bioreactor
- + Less sensitive = suitable for many applications
- + Fast start-up
- + Reasonable operation at 10-15 °C
- High sludge production
- Can be limited by O₂ transfer
- Aeration represents up to 60% of the electricity requirements during WWT
- Safety: aeration can cause spreading of pollutants and microorganisms

Anaerobic

- + Low sludge production (6-8 times less than under aerobic. conditions)
- + Higher energy production
- + No need for aeration
- + Safer
- + No limitation from O₂ diffusion
- Lower biomass productivity
- Sensitive (toxicity, temperature)
- Potential release odorous compounds
- Long start-up
- Need for 2000-3000 mg CaCO₃/L
- Need for High T

Anaerobic/Aerobic

Example of energy balance

Energy (10^6 kJ/d)	Anaerobic	Aerobic
Aeration		- 1.9
Methane	12.5	
Heating to 30°C	- 4.2	
Net Energy	8.3	- 1.9

Metcalf and Eddy (2003): Simulation for wastewater flow 100 m³/d with load 10 kg COD/d

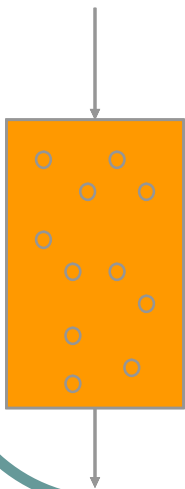
In practice, COD₀ ranges from 300,000-30,000 mg/l are suitable for anaerobic treatment and influents with less than 1300 mg COD/L are typically treated aerobically.

However, there are cases of anaerobic treatment at lower influent strengths!

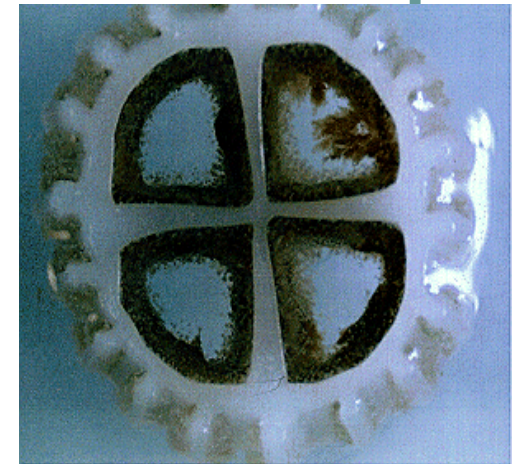
Fixed vs Particle Biofilm



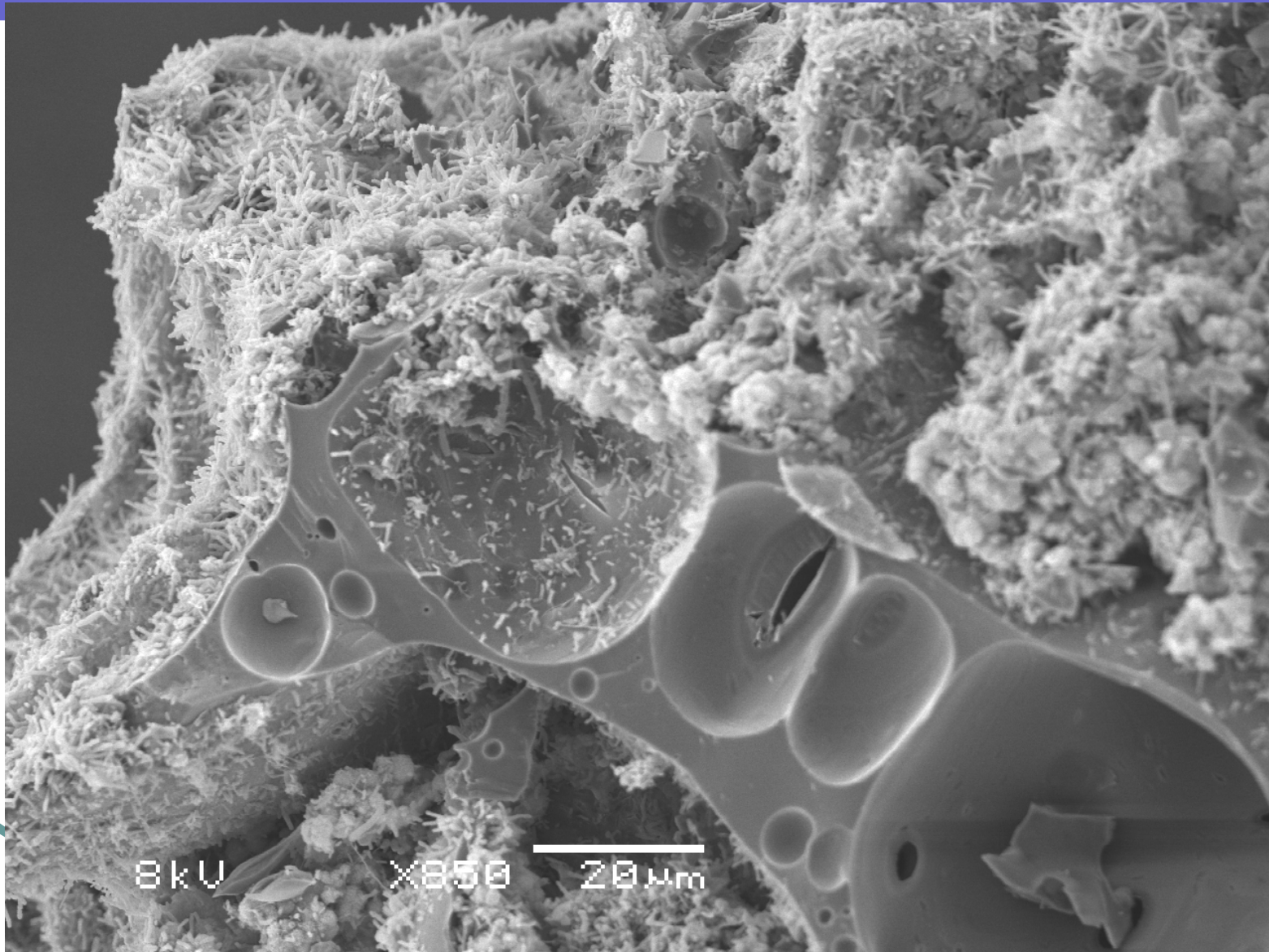
Fixed-film processes favour high cell densities (and cell diversity), long SRT, but are more sensitive to clogging & channelling (heterogeneous conditions). Typically suitable under conditions of slow growth/low biomass productivity (i.e. autotrophs, recalcitrant compounds)



Particle biofilms are less sensitive to clogging and well mixed system. They provide a high active biomass surface area for mass transfer. It can however be hard to suspend or retain particles. Typically used under situations requiring compromise between transfer and activity.



Biofilm



Non-submerged attached-growth processes

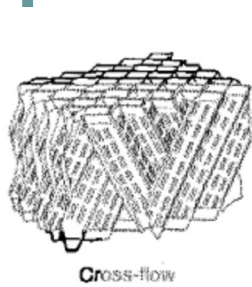
Tricking filters and rotating bioreactors:

- Low energy requirement
- Simple operation (no issue for sludge wasting control)
- No problem with bulking
- Good sludge settling properties

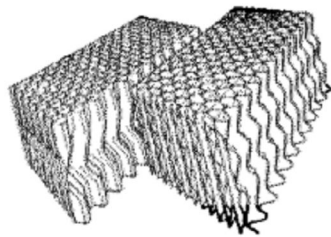
Trickling filters:

- Very diverse microflora (including insects!, anaerobes, etc)
- Problem with odors and low effluent quality if poorly designed
- Long SRT = low biomass production
- Can be limited by O_2 transfer (generally suitable for influents with BOD concentrations lower than 400-500 mg/L)

Non-submerged attached-growth processes



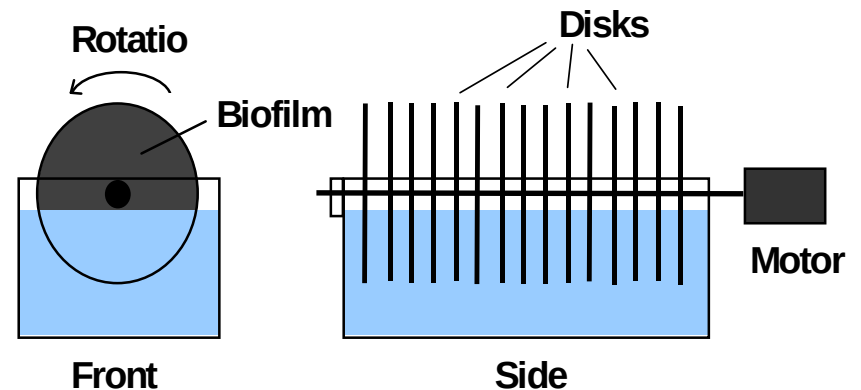
Cross-flow



Tubular



Pall rings



Submerged attached biofilms: i.e. fluidized bed

Main advantages:

Shock loads or non-biodegradable and toxic organics can be adsorbed to an adsorbent (typically activated carbon) used as biofilm carrier

High quality effluent

Submerged bioreactors are often used for industrial wastewater and groundwater treatment.

Remember biofilm processes can be combined with suspended growth process in single or multi-stages processes.

Suspended vs Biofilm

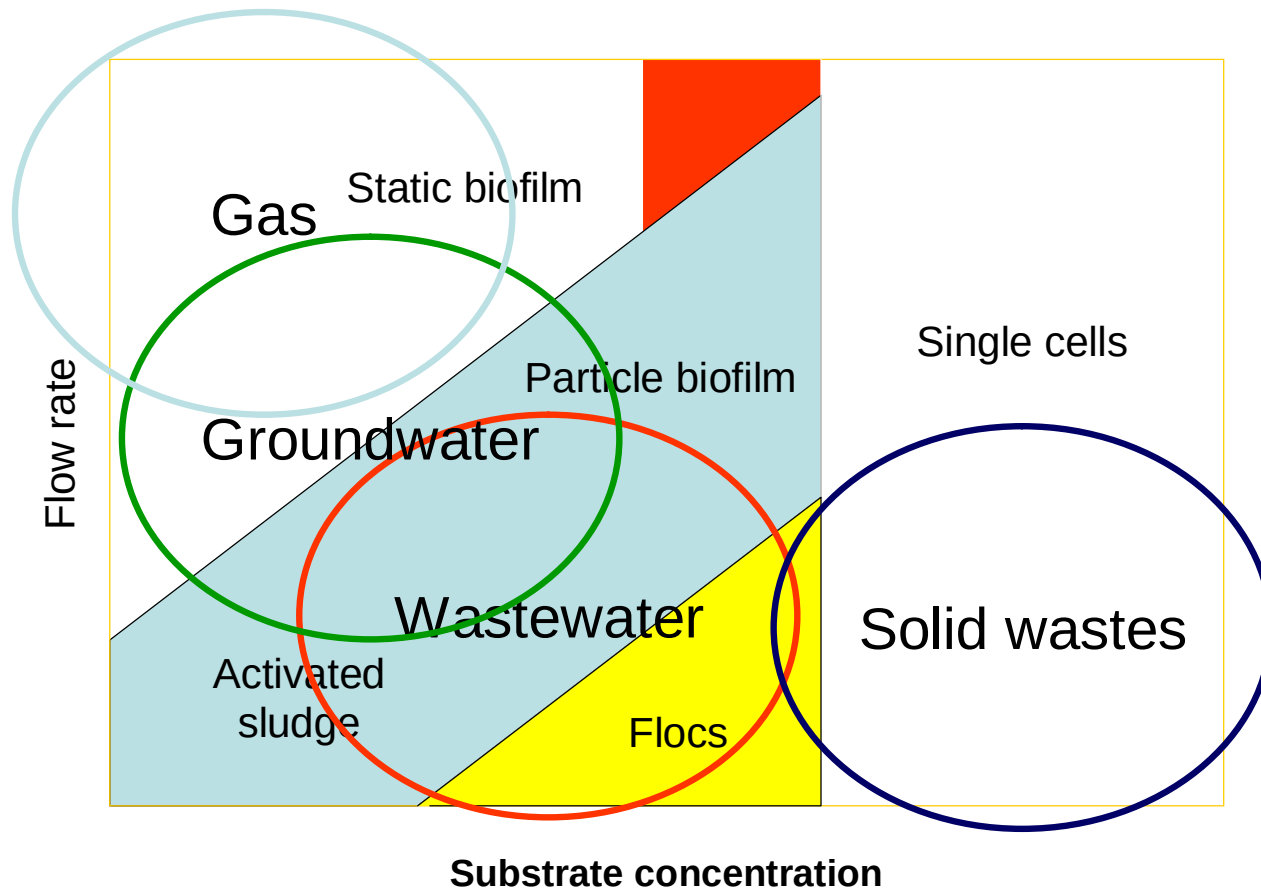
Which configuration is the best is difficult to answer: this will depend on conditions/parameters such as the substrate concentration, the pollutant biodegradability, the required degradation mode (aerobic/anaerobic), etc.

In general, if cell density is the limiting parameter: biofilm systems are better. Examples are poorly biodegradable pollutants (long SRT, need for microbial diversity), autotrophic growth and low substrate concentrations

Biofilm are usually not recommended at high substrate concentrations because of clogging and diffusion (including oxygen supply) problems.

Comparison

Range of application of each bioreactor?



Application to water treatment

What type of treatment (continuous, well-mixed/plug flow, aerobic/anaerobic, activated sludge/biofilm...) would you recommend for the following:

Domestic wastewater city 150 000 PE

Industrial wastewater with Phenolics 5000 mg/L

Groundwater with pesticides 50 mg/L

Non toxic effluent at 300 m³/d with 10 000 mg BOD/L

Comparison

	Criteria	Activated Sludge Plant	Biological filter	Aerated Lagoon	Waste stabilization pond
Plant Performance	BOD Removal	F	F	G	G
	Pathogen removal	P	P	G	G
	SS Removal	G	G	F	F
Economic Factors	Simple & Cheap construction	P	P	F	G
	Simple operation	P	F	P	G
	Land Requirement	G	G	F	P
	Maintenance cost	P	F	P	G
	Energy Demand	P	F	P	G
	Sludge Removal costs	F	F	F	G

General overview

Process	Applications	Advantages	Disadvantages	Cost
Activated sludge	Low/moderate conc.	Simple, proven, good control	Volatile emission, sludge. Aeration costs	+++
Aerated lagoons / ponds	Low conc.	Low costs	Volatile emission, sensitive to shock and climate, land, no control	+
Trickling filter	Low conc., recalcitrant organics	Little sludge, biodiverse	Volatile emission, sensitive to shocks, clogging	+
Anaerobic process	High-strength	Methane production, low sludge	Sensitive to temperature, higher capital costs	++

Conclusions

Most large WWTP are based on activated sludge variations because this is the oldest and best described process. The main design and operating parameter is the SRT (to allow for nitrification and sludge decay to occur).

The trickling filter is used but there are some operational problems (clogging).

Biofilms are more common for gas treatment and anaerobic treatment (USAB).

Ponds are common for secondary treatment at small scales or for tertiary treatment as stabilization ponds.