Aalto University
School of Engineering

Biological treatment processes of water and waste
Lecture 3

WAT - E2180

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Lecture outline

Biological process applications

- Suspended growth
  - Activated sludge
  - Sludge age
  - Design of the process
- Biofilm processes

- DEMO exercise: Activated sludge process design

Removal of organic matter

Nitrogen conversions

- Nitrification
- Denitrification
- Design demo
- Short-cut processes
- N2O

Advanced BACTERIA GAME – Nitrogen removal simulation

Biological processes

Recap of the bacterial growth

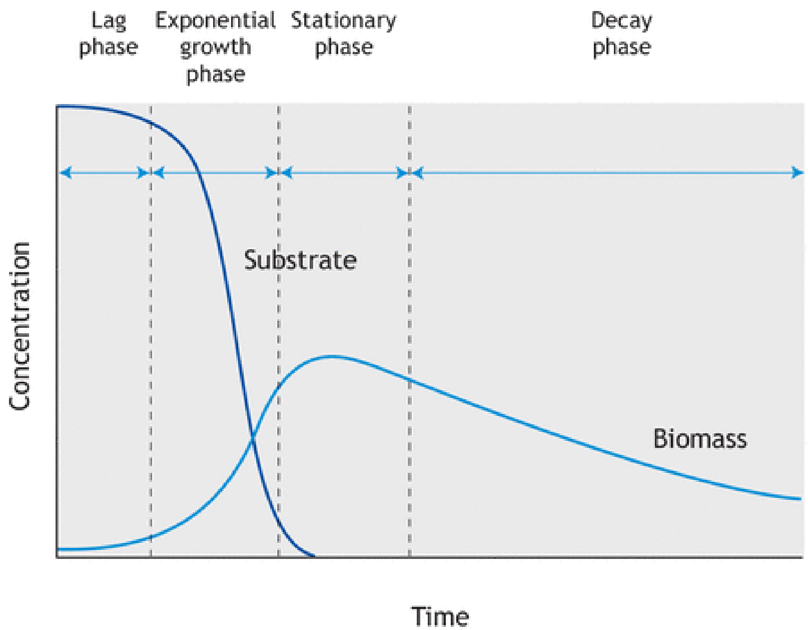


Figure 2.16 Biomass growth in batch mode (adapted from Metcalf & Eddy, 2003)

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

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

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

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

Effect of the influent constituents

Wastewater Constituents				Reaction		Sludge Constituents
Organic	Soluble	Dissolved	Unbiodegradable	Escapes with effluent		
			Biodegradable	Transforms to active organisms		Total settleable solids (TSS); Organic volatile settleable solids (VSS); Biomass in reactor all settleable non suspended
	Particulate	Suspended	Unbiodegradable	Enmeshed with sludge mass		
			Biodegradable	Transforms to active organisms		
		Settleable	Unbiodegradable	Enmeshed with sludge mass		
			Biodegradable	Transforms to active organisms		
Inorganic	Particulate		Settleable	Enmeshed with sludge mass		Total settleable solids (TSS); Inorganic settleable solids (ISS); Inorganic mass all settleable non suspended
			Suspended			
	Soluble		Precipitable	Transforms to settleable solids		
			Biologicaly utilizable	Transfers to	Solids	
					Gas	Escapes as gas
			Non precipitable & Biologicaly utilizable	Escapes with effluent		

→ **ORGANIC MATTER**

- → BIODEGRADABLE – forms new biomass
- → UNBIODEGRADABLE
  - → PARTICULATE – goes to sludge
  - → SOLUBLE – leaves with effluent

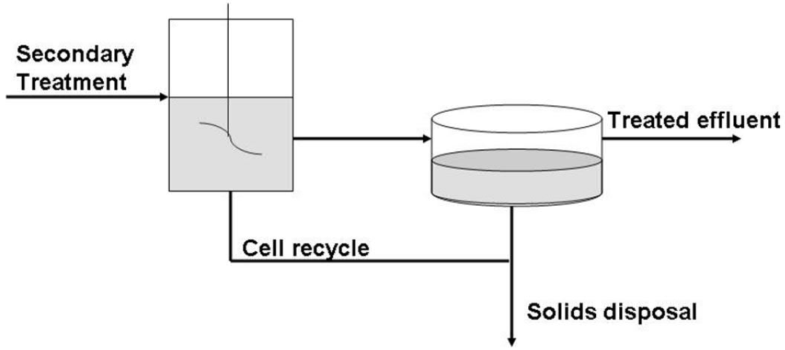
→ **INORGANIC MATTER**

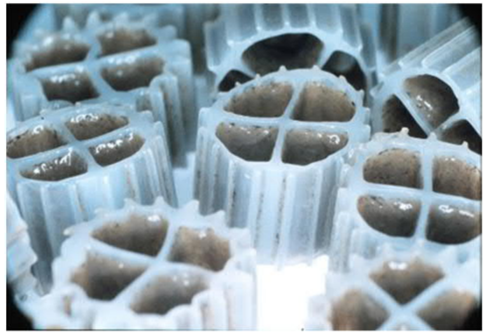
- → PARTICULATE – goes to sludge
- → SOLUBLE – precipitable
  - Biologically utilizable
  - The rest escapes with effluent

How do the biological processes work?

Requirements for a process:

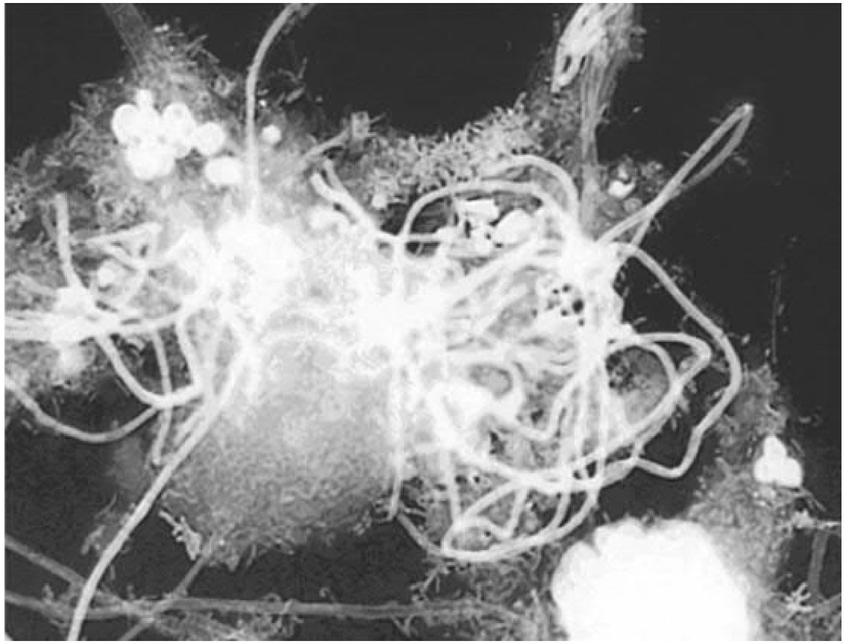
1) **Active microorganisms have to be concentrated within the system**
2) **Microorganisms need to be removed from the effluent before it leaves the system**



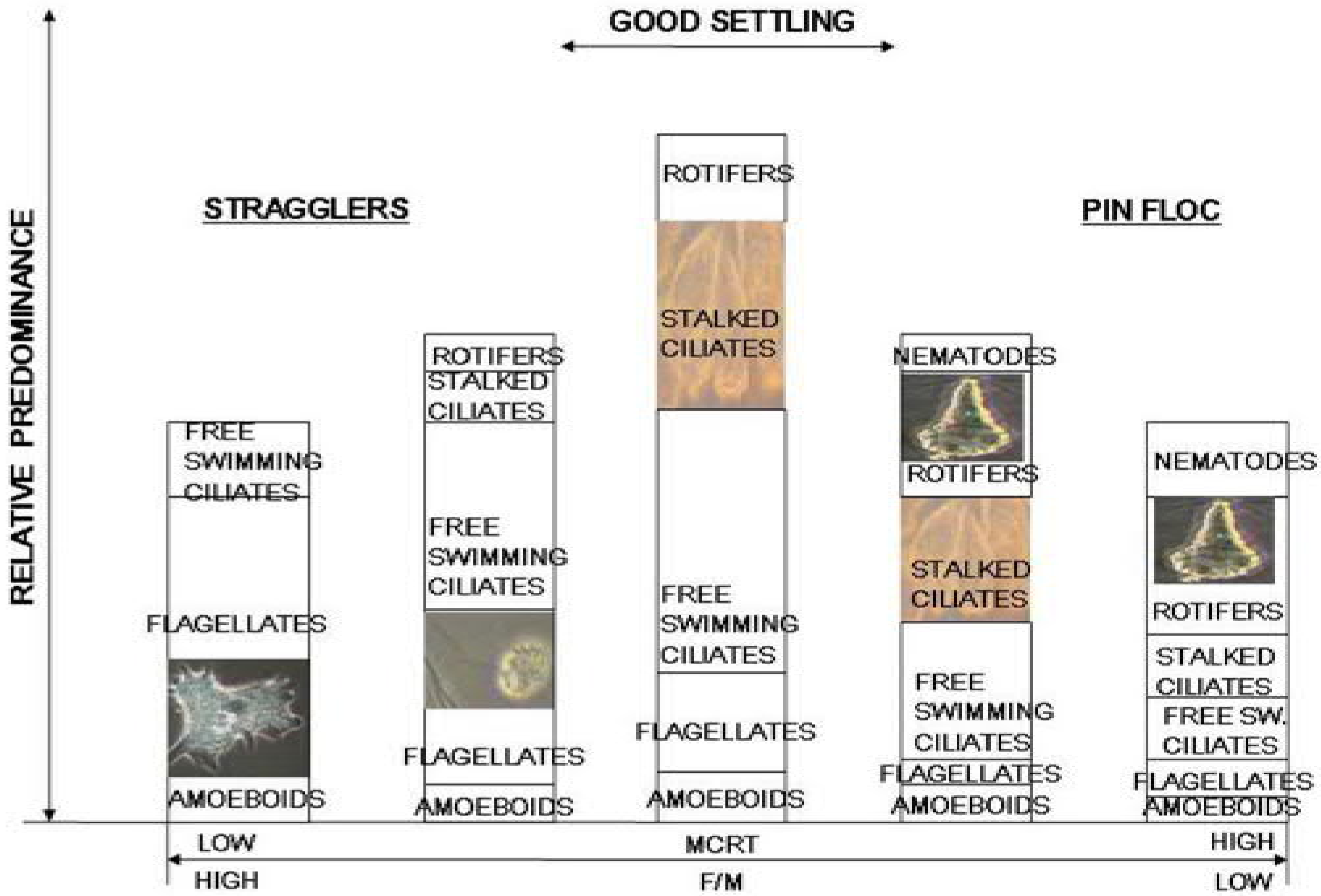


Floc formation of bacteria

- The ”fat reserves” of bacteria are stored on the outside of their bodies.
- This fat layer is sticky and is what the organics adhere to.
- Once the bacteria have “contacted” their food, a hydrolytic enzyme is excreted and it breaks the organic molecules into small units which are able to pass through the cell wall of the bacteria.
- This property of the bacteria is also an asset in settling. The fat on bacteria sticks together and causes flocculation of the non-organic solids and biomass.
- Filamentous bacteria and inert particles form stronger structure for the flocs.



Well settling sludge



Principles of biological processes

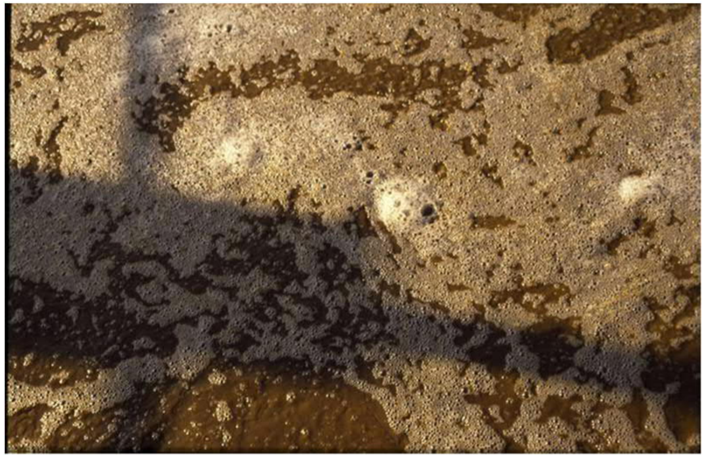
Suspended growth	Biofilm processes
Activated sludge process, membrane bioreactor (MBR)	Moving bed bioreactor (MBBR), biological filters
Sludge is separated in a clarifier (or with a membrane)	No sludge recycle needed, because bacteria are fixed on the carrier material
Sludge recycle	

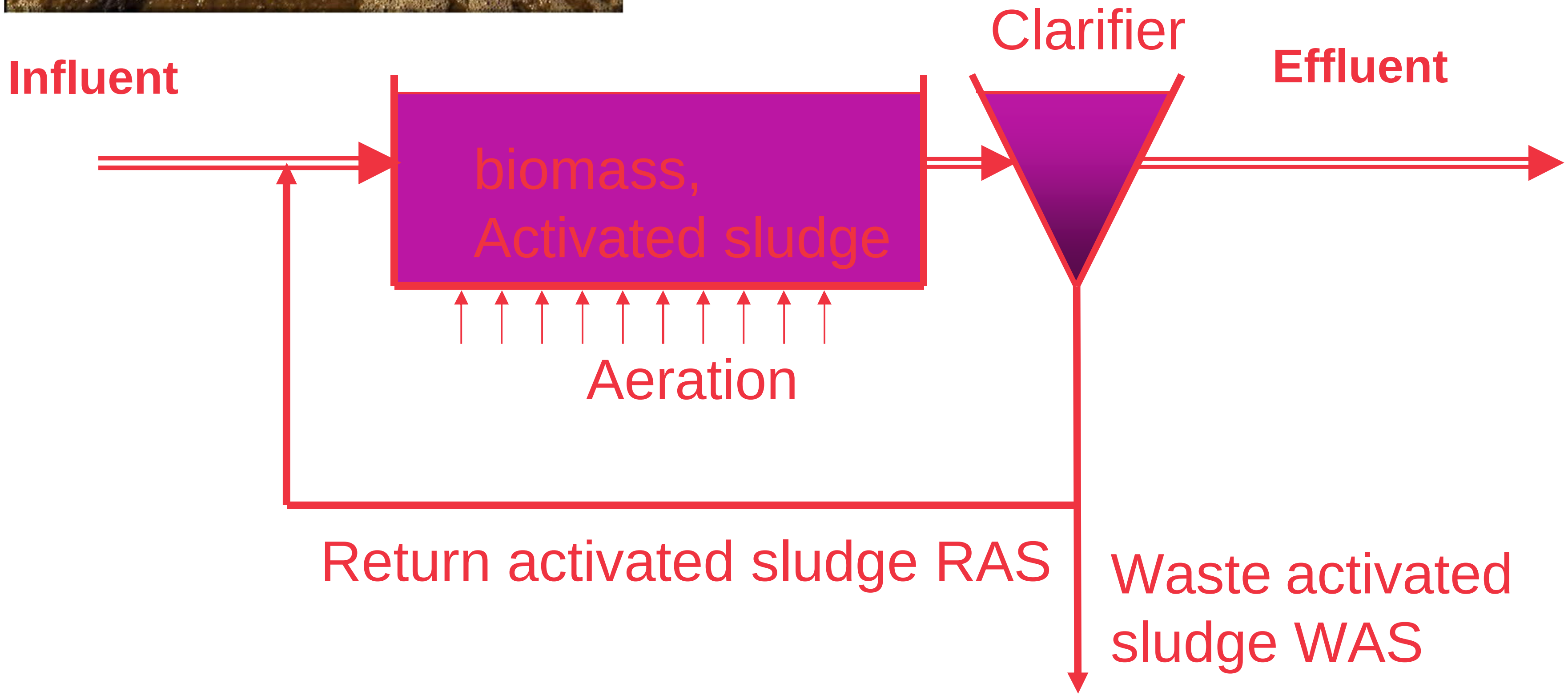
Most commonly only wastewater's own microbes are enriched in the process

Sometimes special kind of bacteria is added
Bioaugmentation is possible

Activated sludge process

Activated sludge process





Activated sludge process

- Aeration basin – oxygen is provided for the microorganisms
- Source of oxygen usually air
- Mixing – with aeration or mixers
- Settling basin – separates the sludge from the water
- Return activated sludge (RAS) recycles most of the sludge back to the aeration basin
- Waste activated sludge (WAS) determines the sludge retention time of the process

Sludge retention time SRT or sludge age

- **The most important parameter in the biological process**

$$\theta_c = V / Q_w$$

$$\theta_c = V X / Q_w X_r$$

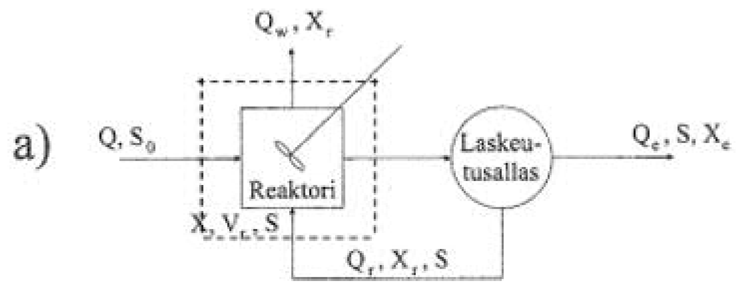
θ_c = Sludge age d (SRT, MCRT)

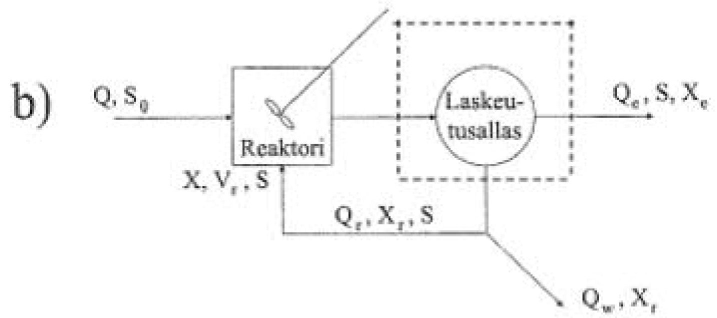
V = Reactor volume m^3

X = MLSS in the reactor kg/m^3

Q_w = WAS flow rate m^3/d

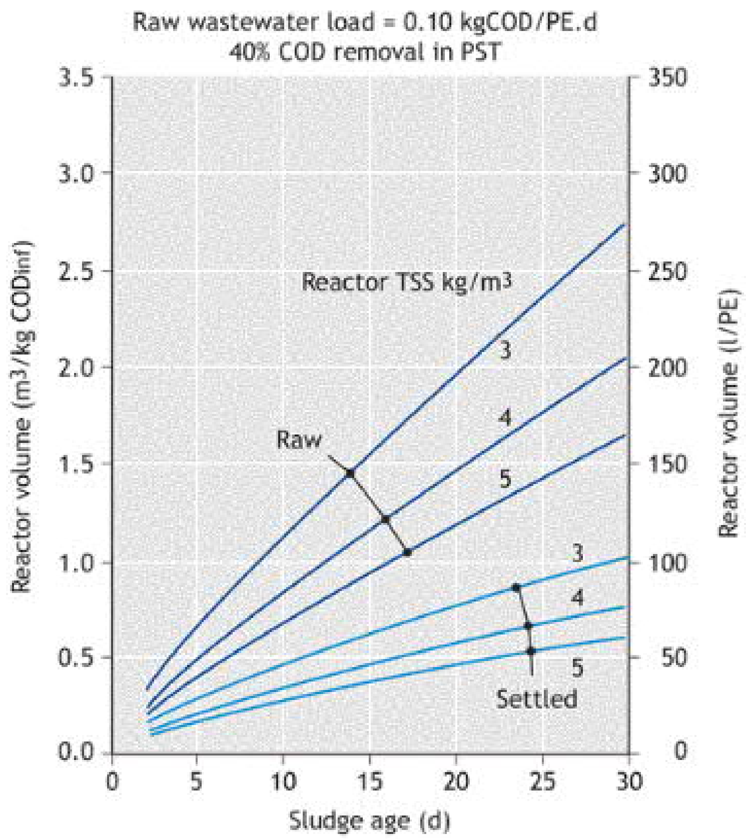
X_r = MLSS in RAS kg/m^3





Sludge age

- **Sludge age determines the reactor volume and sludge concentration**
- **It determines also the biological performance**
  - Short (1-5 days) – only COD removal
  - Intermediate (10-15 days) – COD removal + nutrient removal
  - Long (>20 days) – COD + nutrient removal, enhanced micropollutant removal



Important parameters of activated sludge

- **In bioreactor:**
  - Sludge concentration (MLSS) g/l = X (or MLVSS!!)
  - Sludge age (SRT)
  - Volumetric loading = BOD-load / reactor volume (kgBOD/m^{3}d)
  - Sludge loading = F/M = BOD-load / V · X (kgBOD/kgMLSSd)
  - Sludge yield (kgSS/kgBOD)
  - Hydraulic retention time
- **In settling**
  - Sludge volume index SVI
  - Surface loading = flow rate / surface area (m/h)
  - Sludge surface loading (SSL) = flow rate · X / surface (kgSS/m^{2}d)
  - Sludge volumetric loading = SVI/1000 ·SSL (m^3/m^{2}h)

Dimensioning of activated sludge process

- **First decide which sludge age is needed**
  - Short SRT< 5d → only COD removal
  - Long SRT > 10d → nitrification

Steps:

→ Select the sludge age, take into account the temperature effect

→ The biomass produced is calculated with the following:

→ $Y_{OBS} = Y / 1+b\theta_c$ (or this is known from experience)

→ $XV = \theta_c \, Q \, Y_{OBS} \, (S_0 - S_e)$ → select the MLSS and calculate the volume.

- Often used also: dimensioning based on volumetric loading or sludge loading; use of safety factors
- COD removal: 0,5 – 1 kgBOD/kgMLSSd, nitrification 0,04 – 0,1 kgBOD/kgMLSSd (or < 0,3 kgBOD/m3)

DEMO EXERCISE: LOHJA PITKÄNIEMI WWTP

The plant has two bioreactors in two lines, together 3600 m^3. Two thirds are anoxic Settling surface area is 1150 m^2. Influent flow rate is 8090 m^3/d and the BOD concentration in the influent is 305 mg/l. Slusge concentration MLSS is 7 g/l.

Calculate the hydraulic retention time, volumetric loading and sludge loading in aeration. Do you think nitrification is occuring in the process?

Waste activated sludge WAS is removed directly from the aeration basin. Flow rate is 300 m^3/d. Calculate the sludge age. Based on the sludge are what could you say about nitrification now?

Hydraulic retention time = 3600 / 8090 d = 0,44 d = 10,7 h.

Volumetric loading = 8090 * 305 / 3600 $gBOD_7$ /m^3 d = 685 $gBOD_7$ / m^3 d = 0,67 kg BOD_7 / m^3 d

Sludge loading = 8090 * 305 / (3600 * 7) $gBOD_7$ / kg MLSS d = 98 $gBOD_7$ / kg MLSS d = 0,98 $kgBOD_7$ / kg MLSS d.

Based on the volumetric loading, nitrification is not occuring. Based on the sludge loading nitrification might occur.

SRT (when WAS is removed from the reactor) = reactor volume / WAS flow rate (m3/d) = 3600 / 300 = 12 d.

Looks promising but aerobic SRT is important for nitrification, so in this case nitrification is not working efficiently.

Activated sludge process

- Based on microbiological activity in aerobic conditions
- Heterotrophic microbes degrade the organic matter to CO_2 and H_2O
- Nutrient are assimilated during the biomass growth
  - $BOD_{7,ATU}$:Nkok:Pkok = 100:5:1
  - => nutrient removal (N,P) ~20-30 %

Basic version

- Autotrophic microbes are oxidazing NH_4
- Nitrogen removal: Denitrifying bacteria + anoxic zone
- BioP: PAOs + anaerobic zone

Biofilm processes

Biofilm processes

- Biomass is growing on carriers
- Processes/Terms:

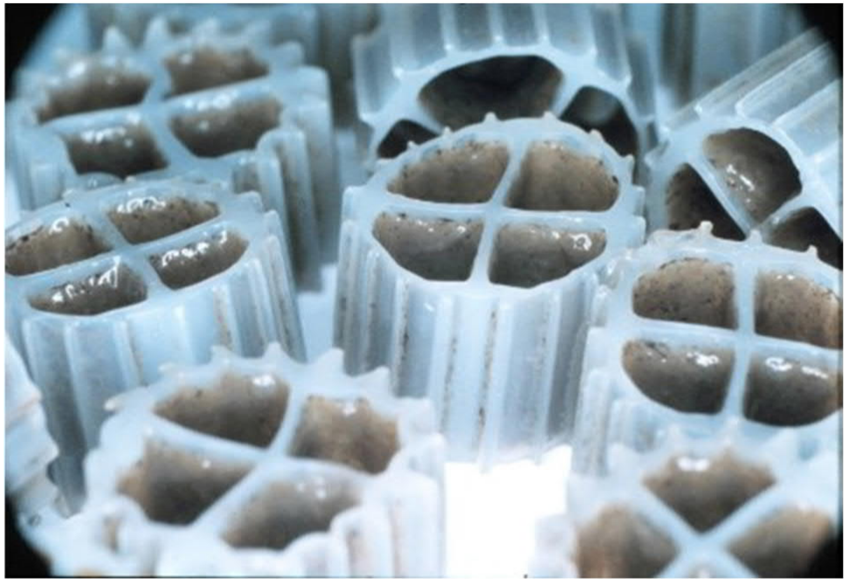
MBBR (Moving bed biofilm)

IFAS (Integrated fixed-film activated sludge) = MBBR with sludge recycling

Trickling filter

Biological filter

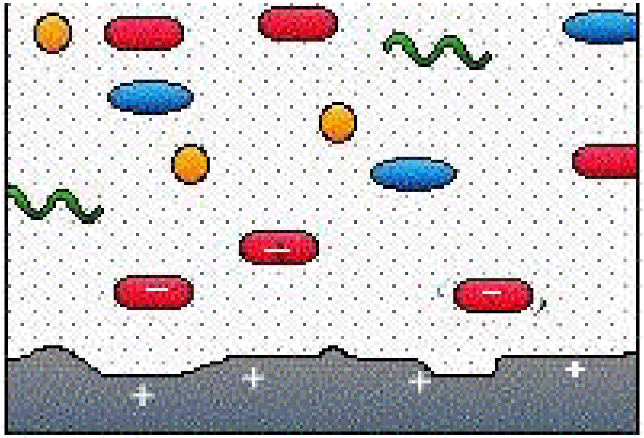
Biorotor



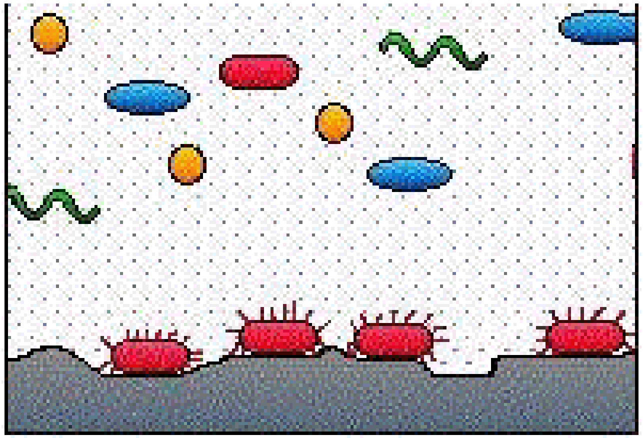
Biofilm

- On any kind of surface, microbes will attach and start to grow as long as there are water and nutrients available = biofilm grows

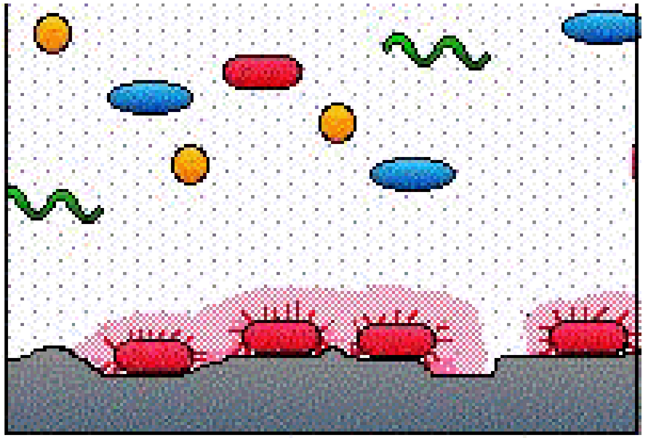
Biofilm



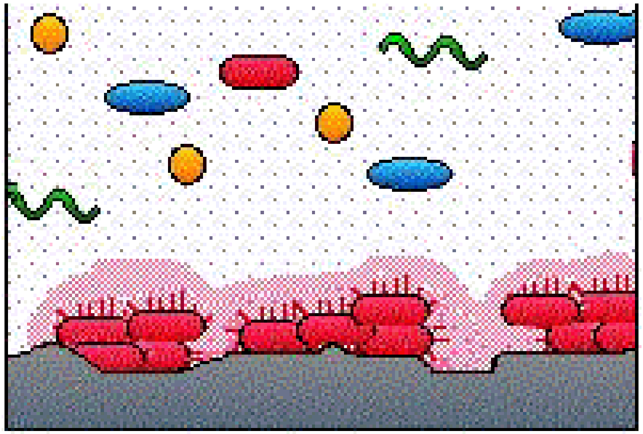
Biofilm



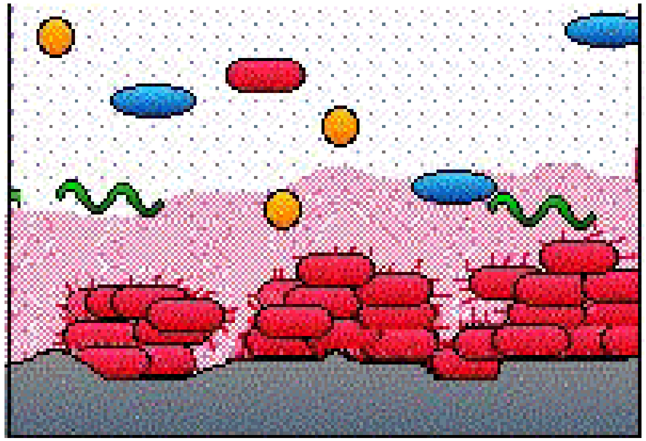
Biofilm



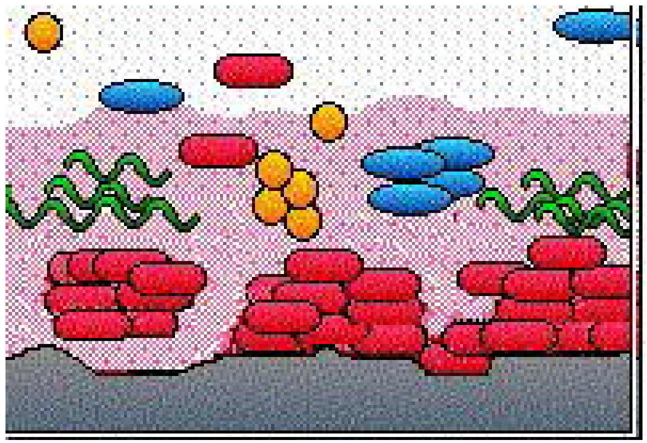
Biofilm



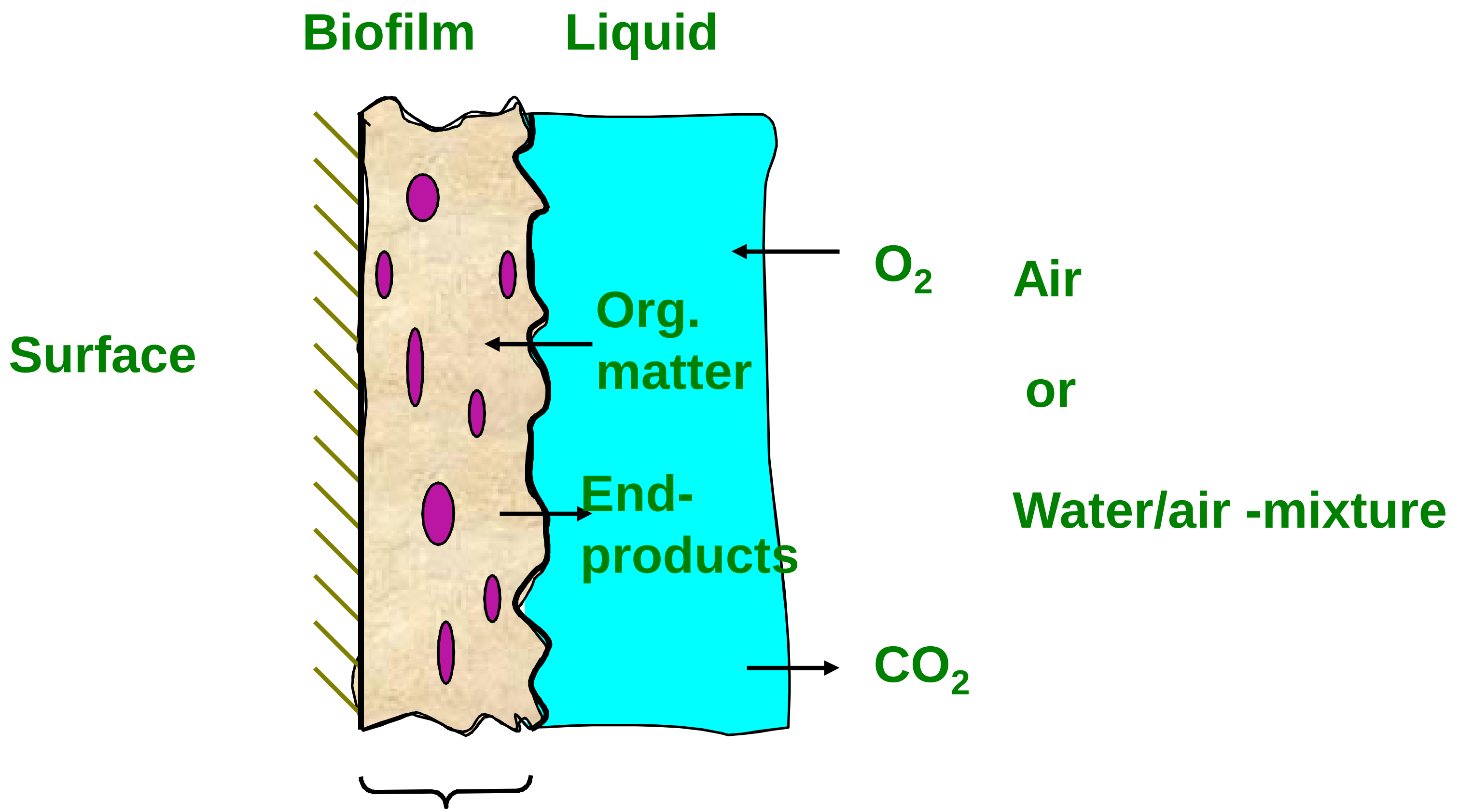
Biofilm



Biofilm



Structure of biofilm



- Efficient thickness appr. 100 µm

Structure of biofilm

Microbes are protected inside the biofilm

MBBR in large scale

Pictures: Odegaard 2014

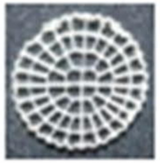
MBBR

- 500 m^2/m^3 bulk
- 9.1 x 7.2 mm diameter/depth

K1

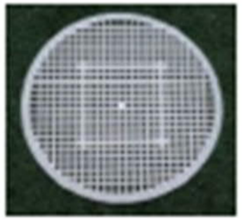
- 500 m^2/m^3 bulk
- 25 x 10 mm diameter/depth

K3



- 800 m^2/m^3 bulk
- 25 x 3.5 mm diameter/depth

K5



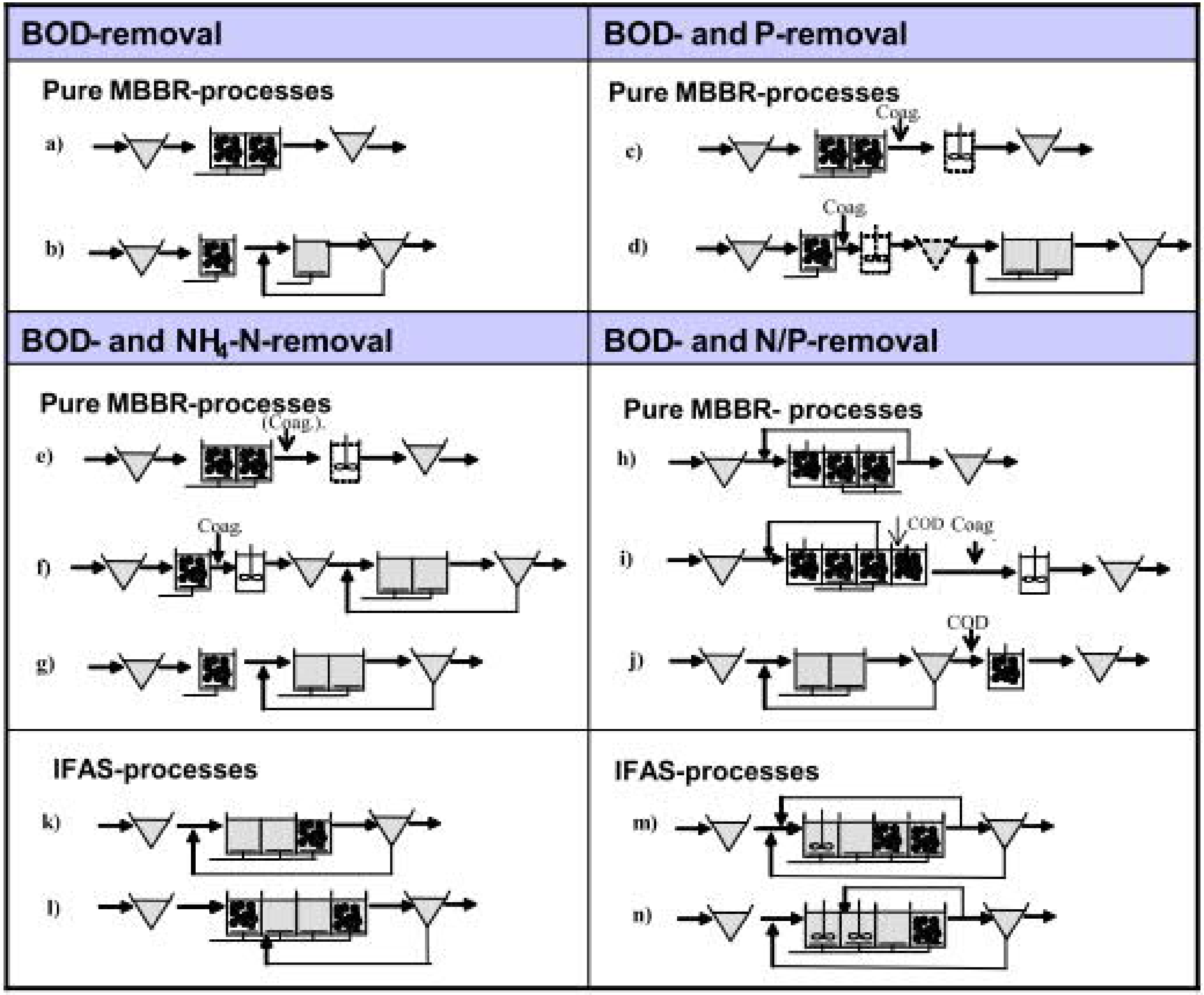
- 1200 m^2/m^3 bulk
- 48 x 2.2 mm diameter/depth

BiofilmChip M

Pictures: Odegaard 2014

MBBR – important parameters

- Different carrier have different surface areas
- Typically 500 – 800 m^2/m^3
- Reactors are not full of carriers - 40 – 60 % → specific max filling rate for each carrier
- The carriers have a density of a bit less 1 g/cm^3
- Carriers are mixed using air bubbles and mixers
- Aeration typically with course bubble aerators
- MBBR fans claim that oxygen transfer is improved by the carriers(?)



Kuvat: Odegaard 2014

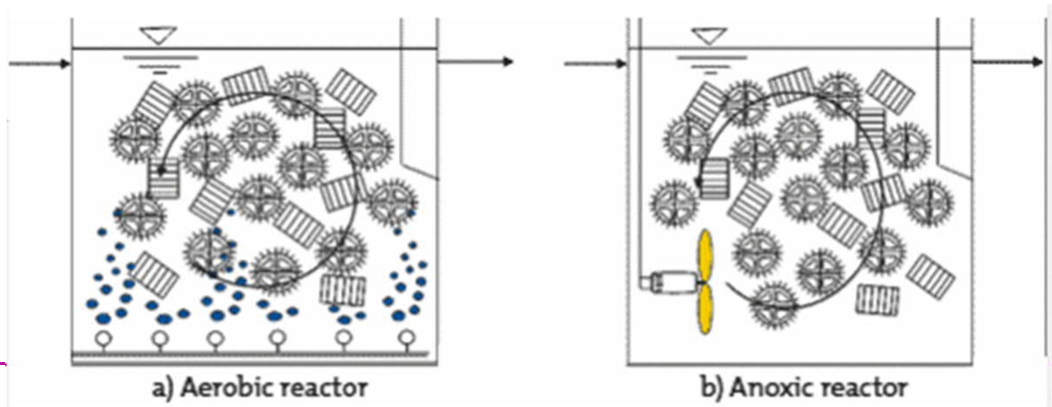
Solid separation in MBBR

- MBBR effluent typically contains 150-500 mgSS/l (>90 % of the biomass stays on the carriers)
- Typically two types of flocs: : large flocs (30 – 300 um) and very small particles (alle 1 um)
- Small particles require chemical flocculation
- Solid separation can be done with settling, flotation, sand filtration,…

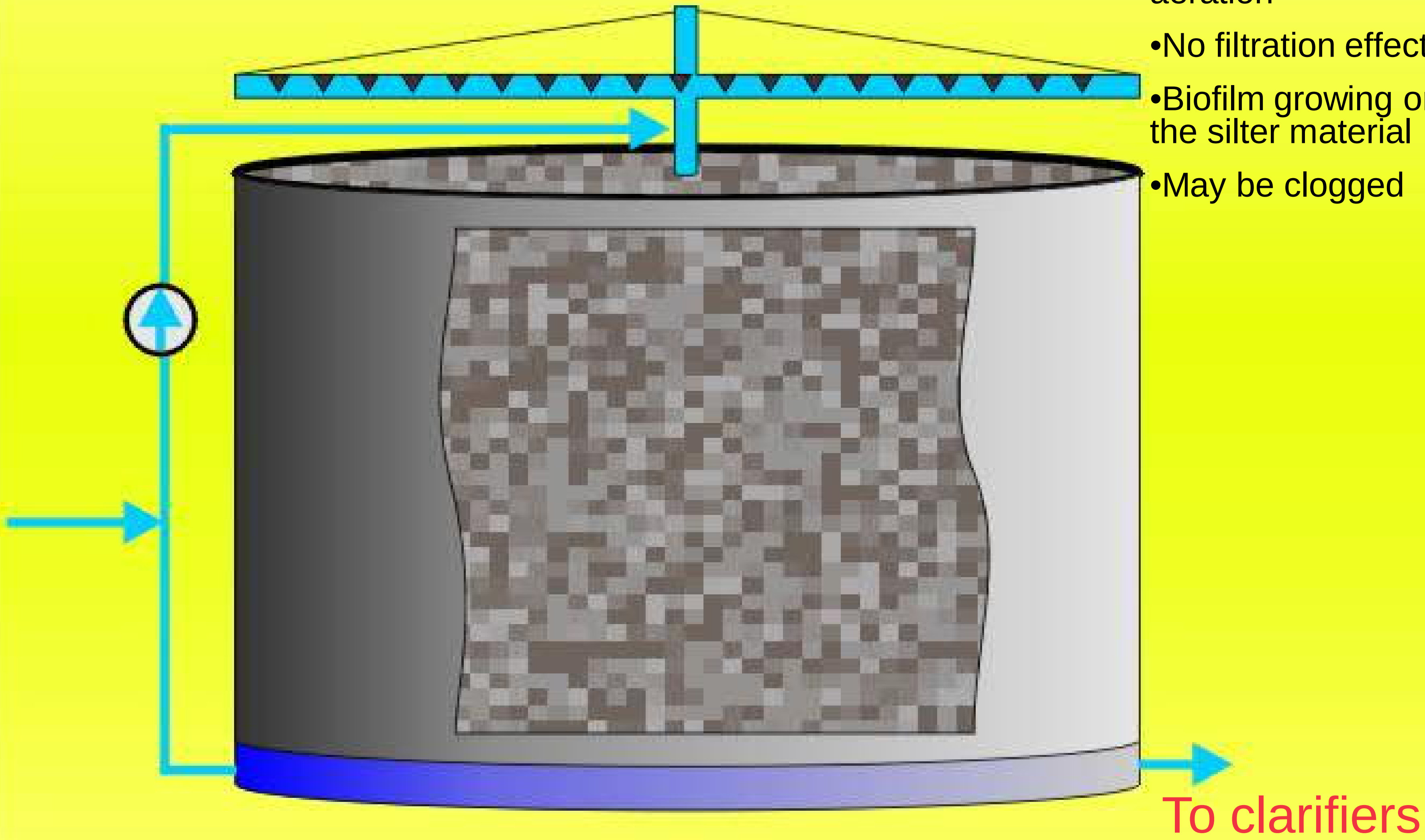
WHY MBBR?

- Smaller sludge production
- Sludge easily dewaterable
- Process stands well variations in temperature and in other conditions
- Space savings

- Requires more energy if nitrification is needed

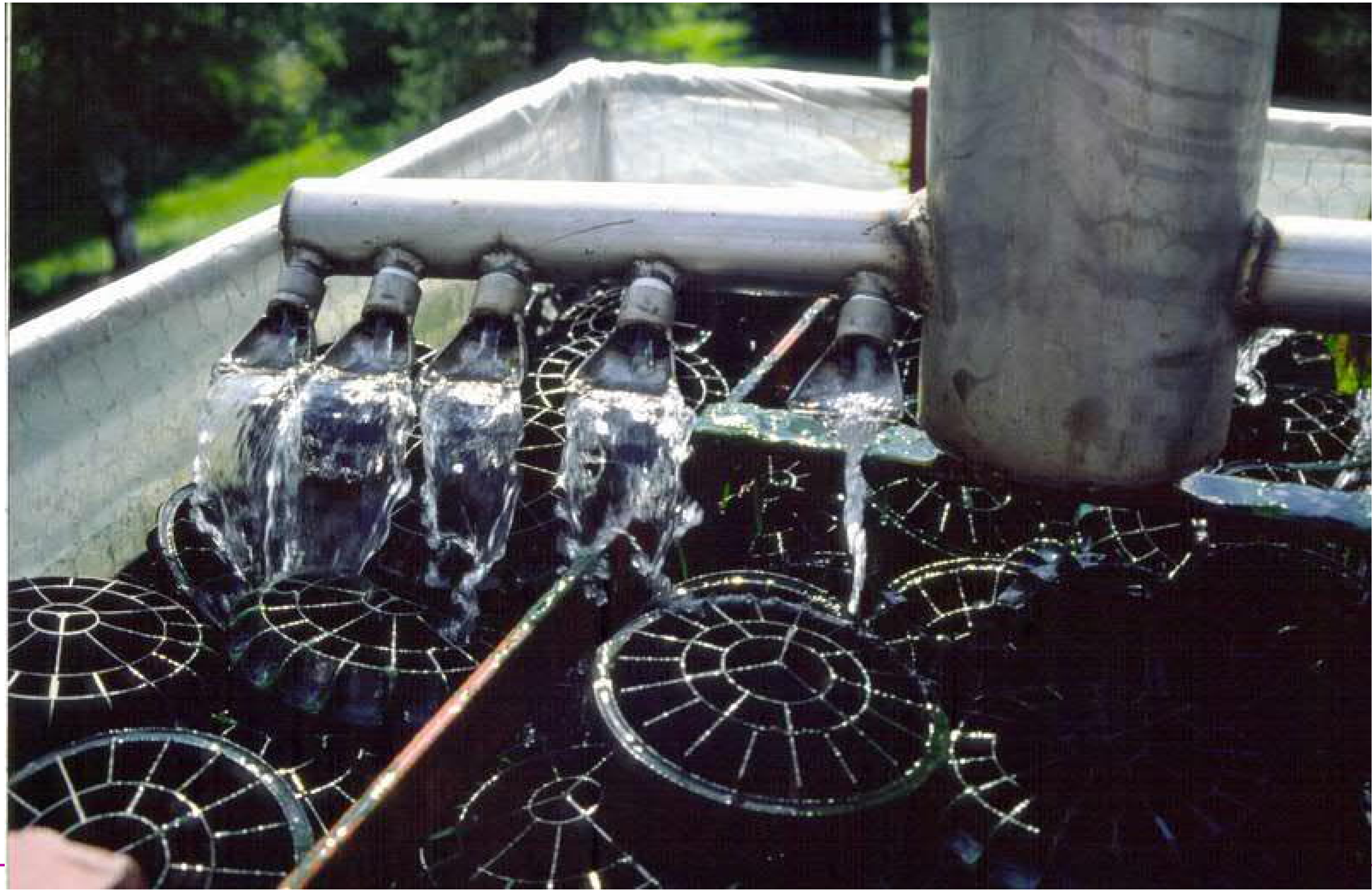


Trickling filter



- •Water recycle=> no aeration
- •No filtration effect
- •Biofilm growing on the silter material
- •May be clogged

Trickling filter



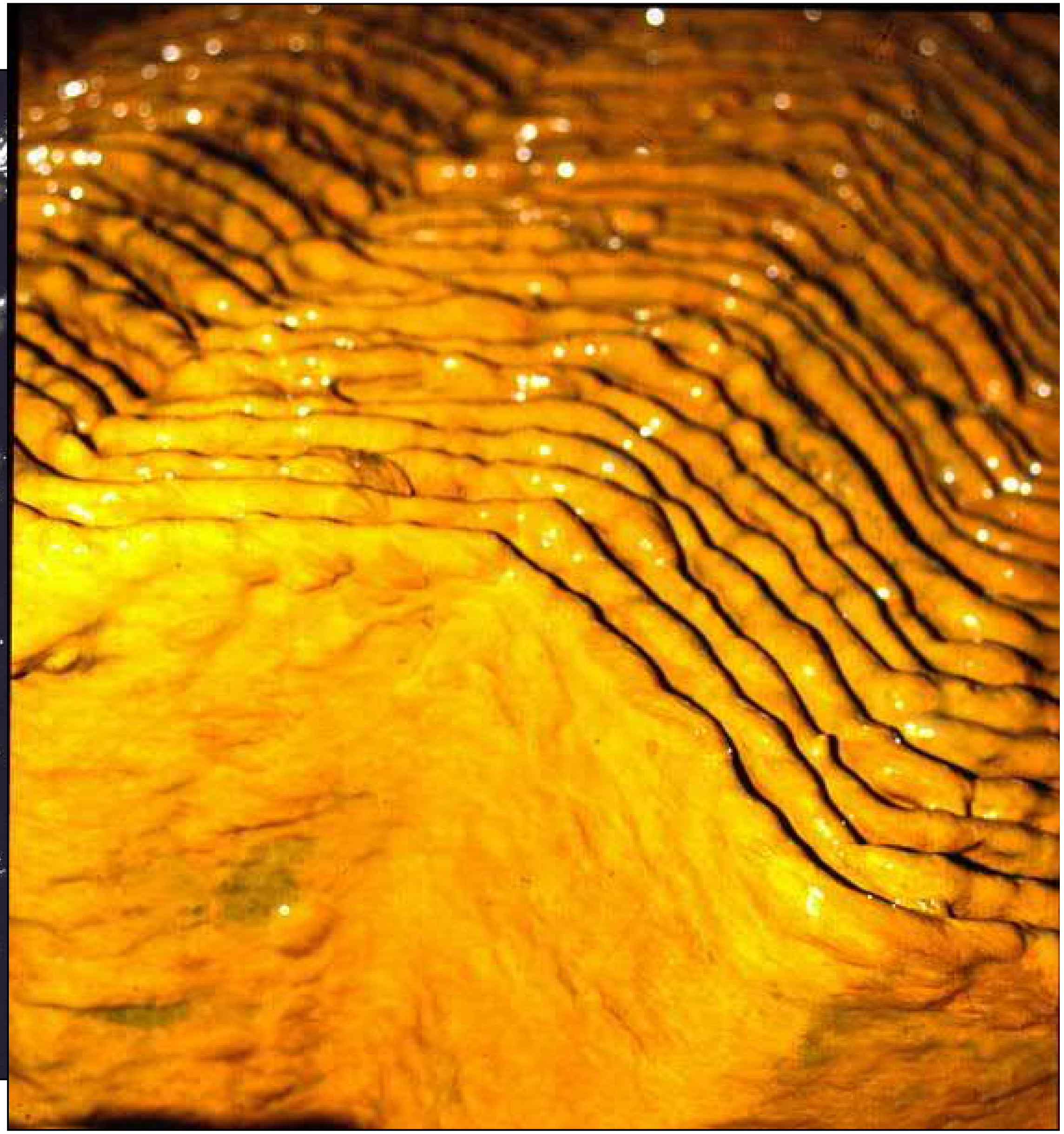
Finnish Ufox-carrier

Trickling filter Metallostroi, St. Petersburg

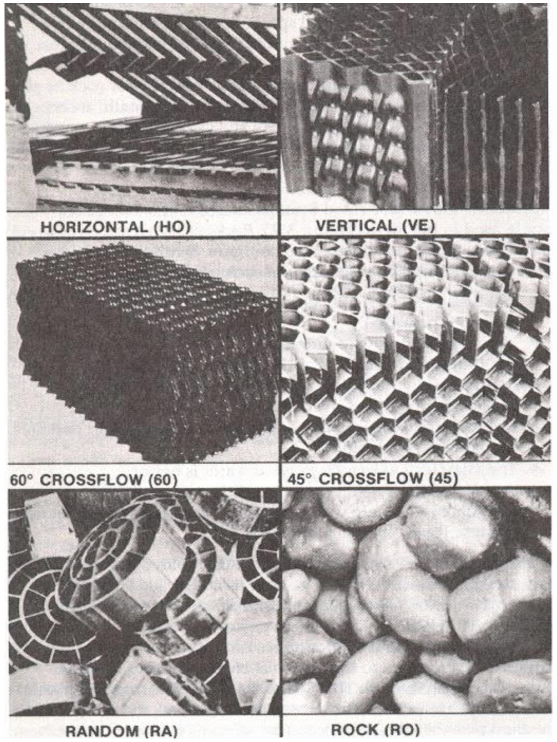
Aalto University
School of Engineering

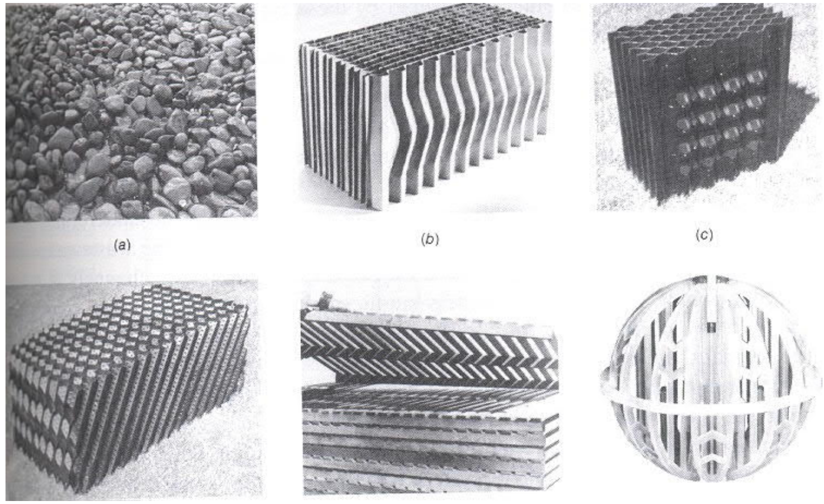
Biorotor

Biorotor



Examples of different carrier material

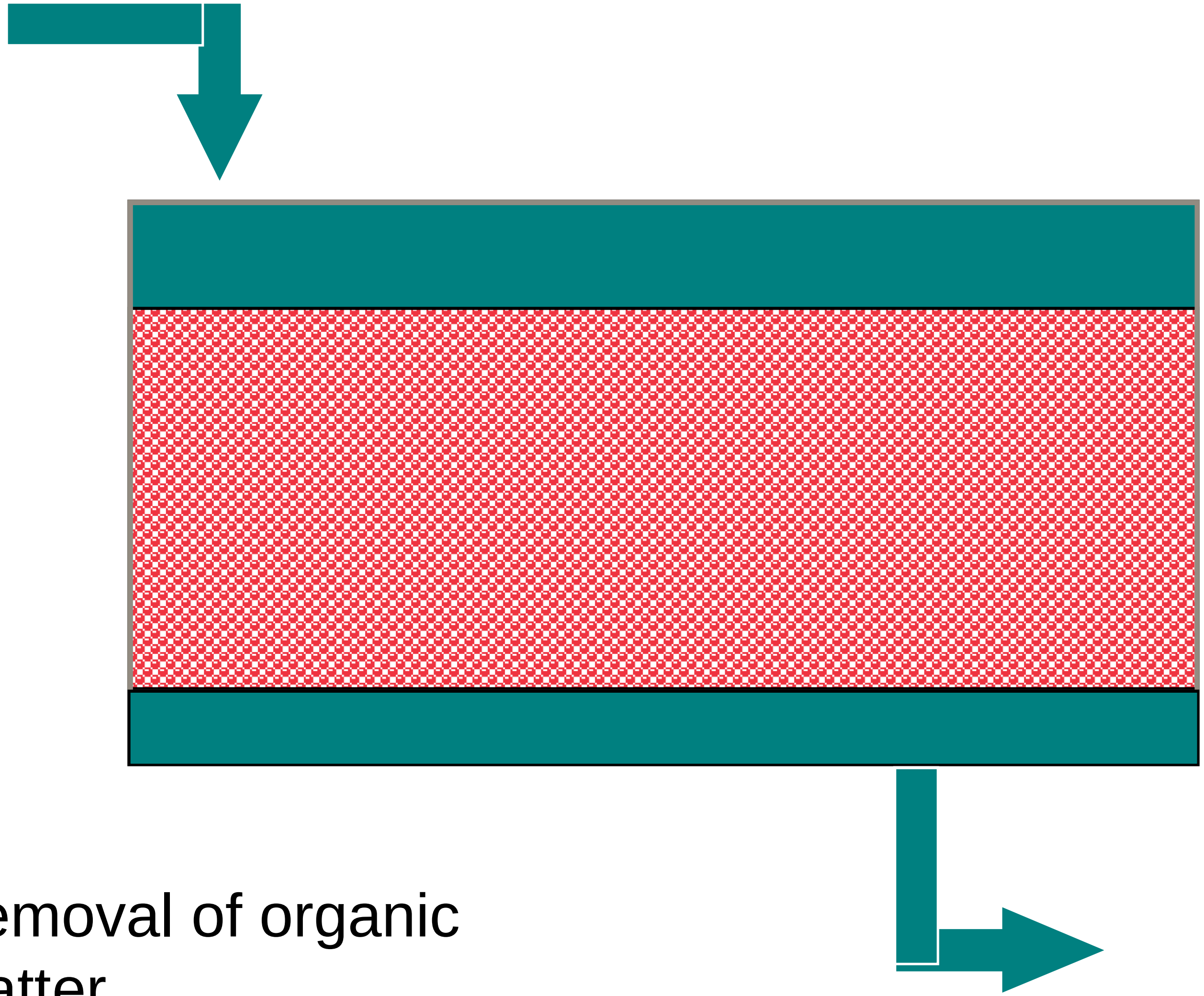




Biological filter

- Biological treatment + physical filtration
- Removal of BOD, SS, P, nitrification, denitrification
- Often the last process step (tertiary)
  - Can be also used as the main process
- Filter material e.g.. sand, grit, small balls of polystyrene
- Filter is back-washed
  - Washwater 2 – 5 % of the treated wastewater
  - The quantity of biofilm can be controlled (unlike in trickling filter)

Biological filter down-flow

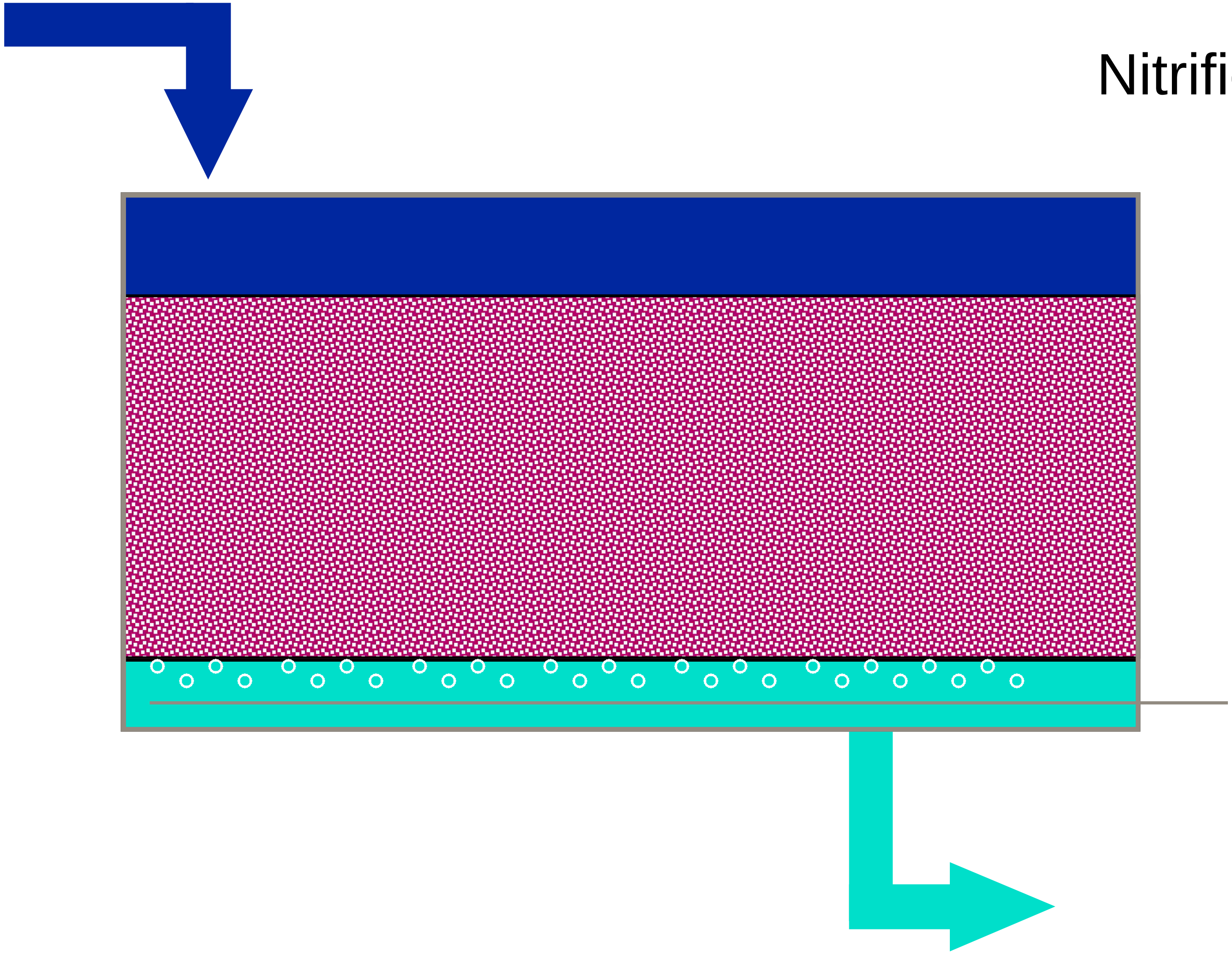


Removal of organic matter

Biological filter

down-flow

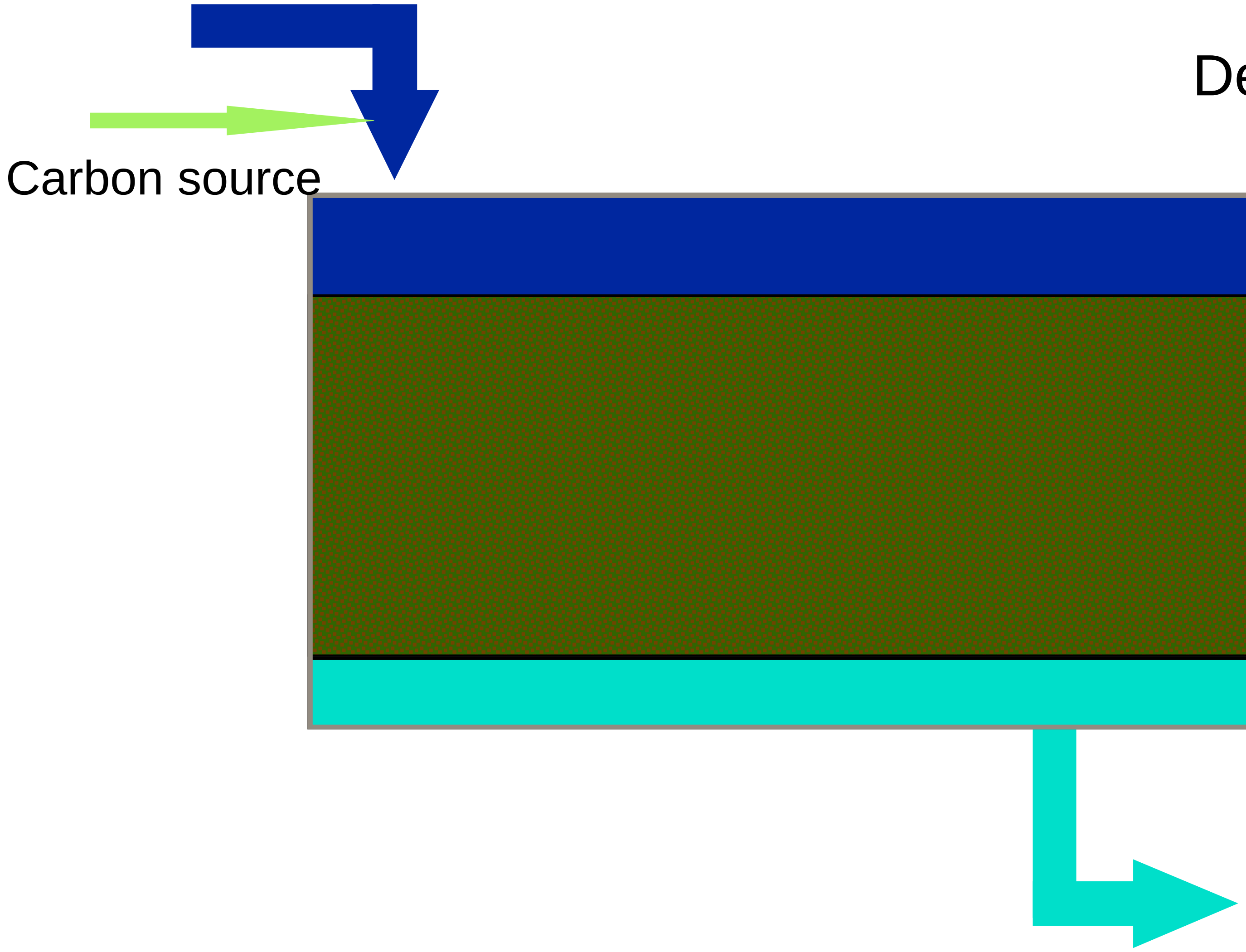
Nitrification



Biological filter

down-flow

Denitrification



Nitrogen conversions

Assimilation

Nitrogen: Assimilation, anabolic substrate

Protein are the major dry component on a living cell, 5...15%.

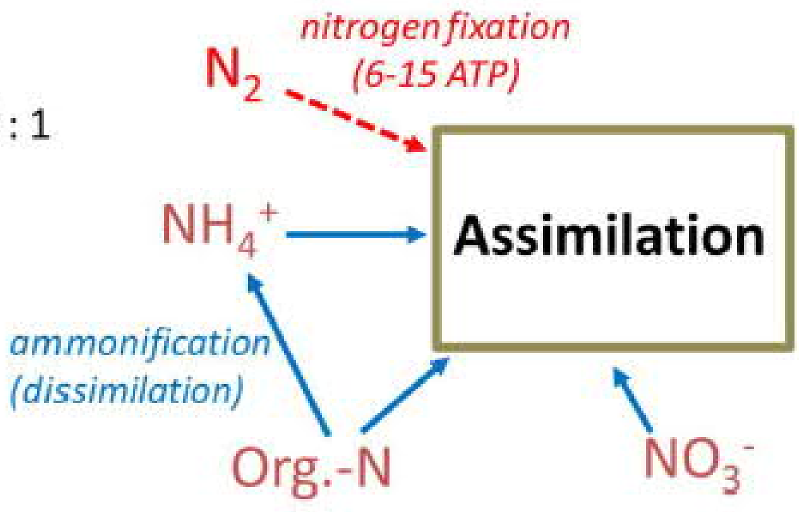
(Amino)Nitrogen is one of the main components of protein,

but also in RNA, DNA ...

In fresh bacteria mass: C:N:P = 50 : 10 : 1

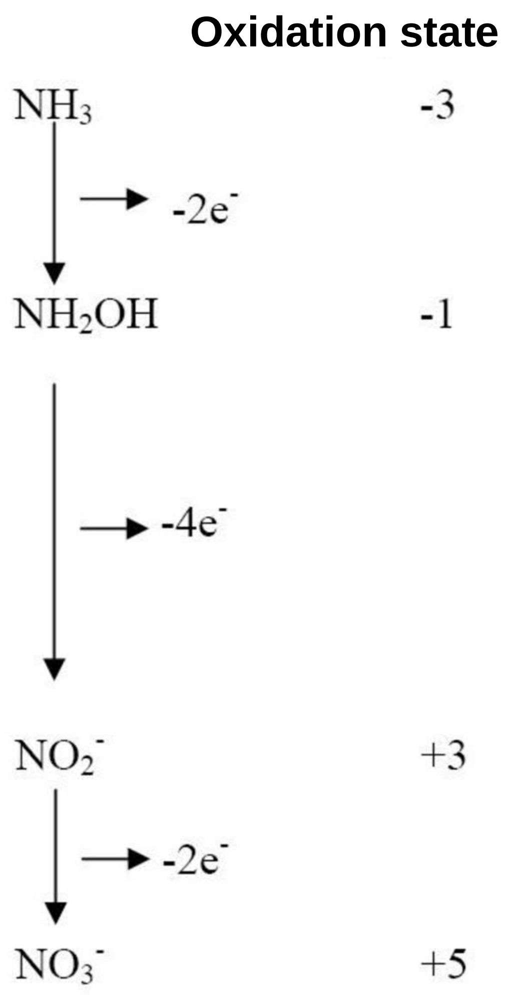
In aerobic wastewater treatment:

BOD5:N:P = 100:5:1

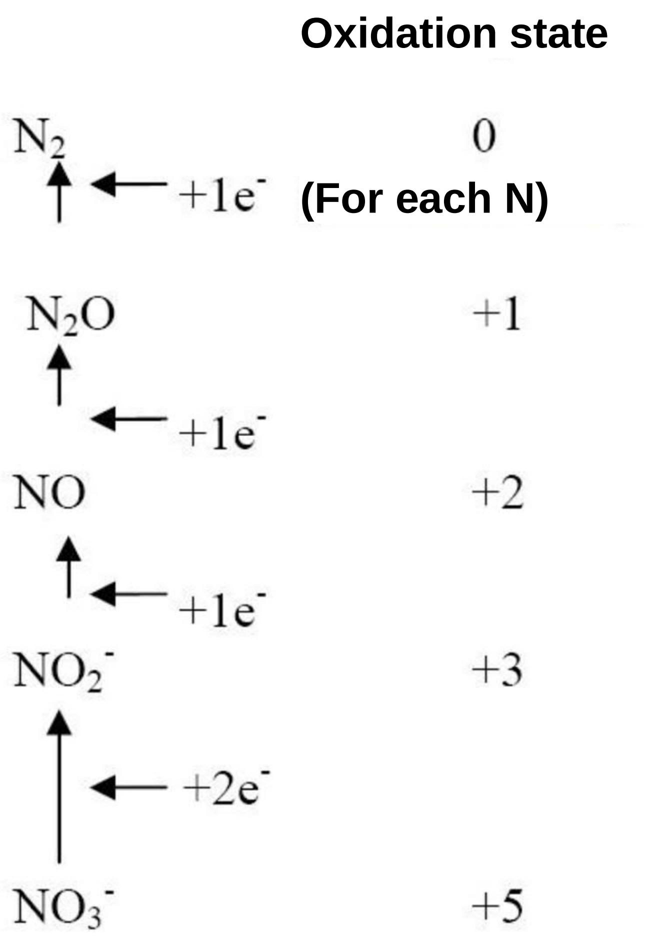


Nitrogen removal

Nitrification (oxidation)



Denitrification (reduction)



Nitrification and denitrification

- Nitrification in two steps

1. $2\ NH_4^+ + 3\ O_2 \rightarrow 2\ NO_2^- + 2\ H_2O + 4\ H^+$ (nitritation)
2. $2\ NO_2^- + O_2 \rightarrow 2\ NO_3^-$ (nitratation)

- Denitrification in four steps

Denitrification generally proceeds through some combination of the following intermediate forms:

$$NO_3^- \rightarrow NO_2^- \rightarrow NO + N_2O \rightarrow N_2\ (g)$$

The complete denitrification process can be expressed as a redox reaction:

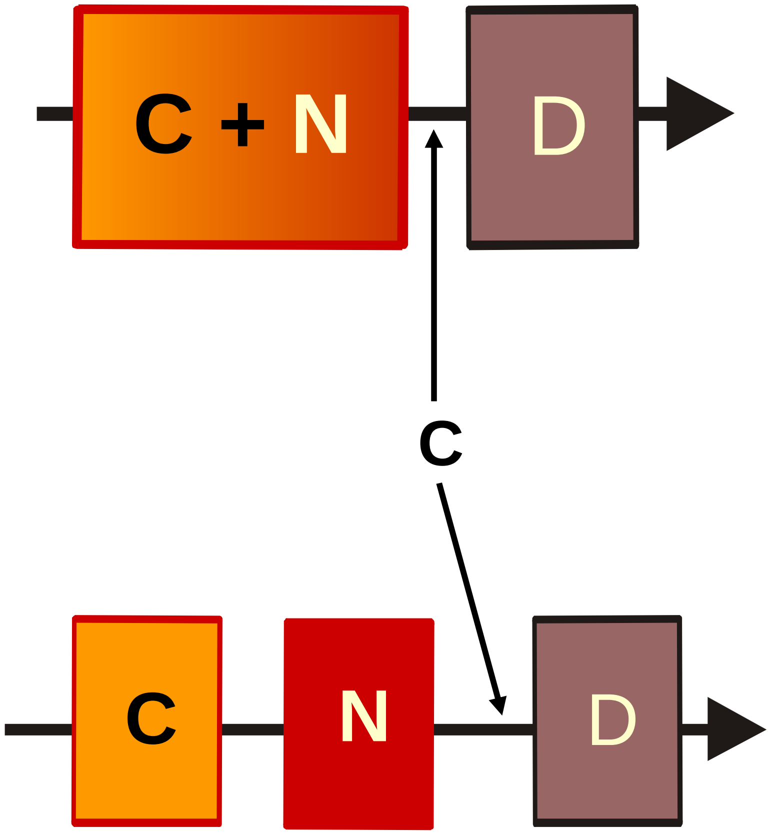
$$2\ NO_3^- + 10\ e^- + 12\ H^+ \rightarrow N_2 + 6\ H_2O$$

Nitrification and denitrification

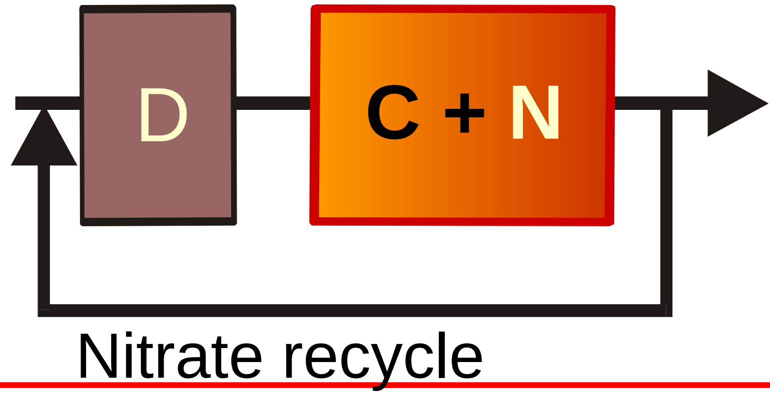
SRT	long SRT	short SRT increases the rate
Oxygen	high, min 2 mg/l	no oxygen or very low
Organic matter	no need (autotrophic)	needs a carbon source
BOD load	low load	high load
Alkalinity	consumes	produces

Process options – N removal

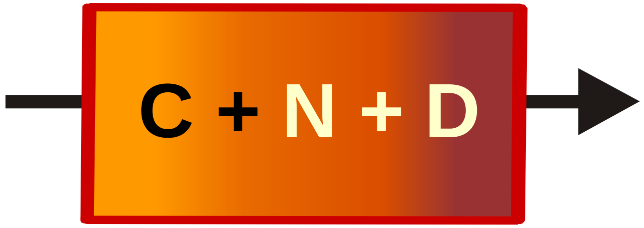
ND processes



DN- processes (recycle)



Sequenced reactors



Comparison of different configurations

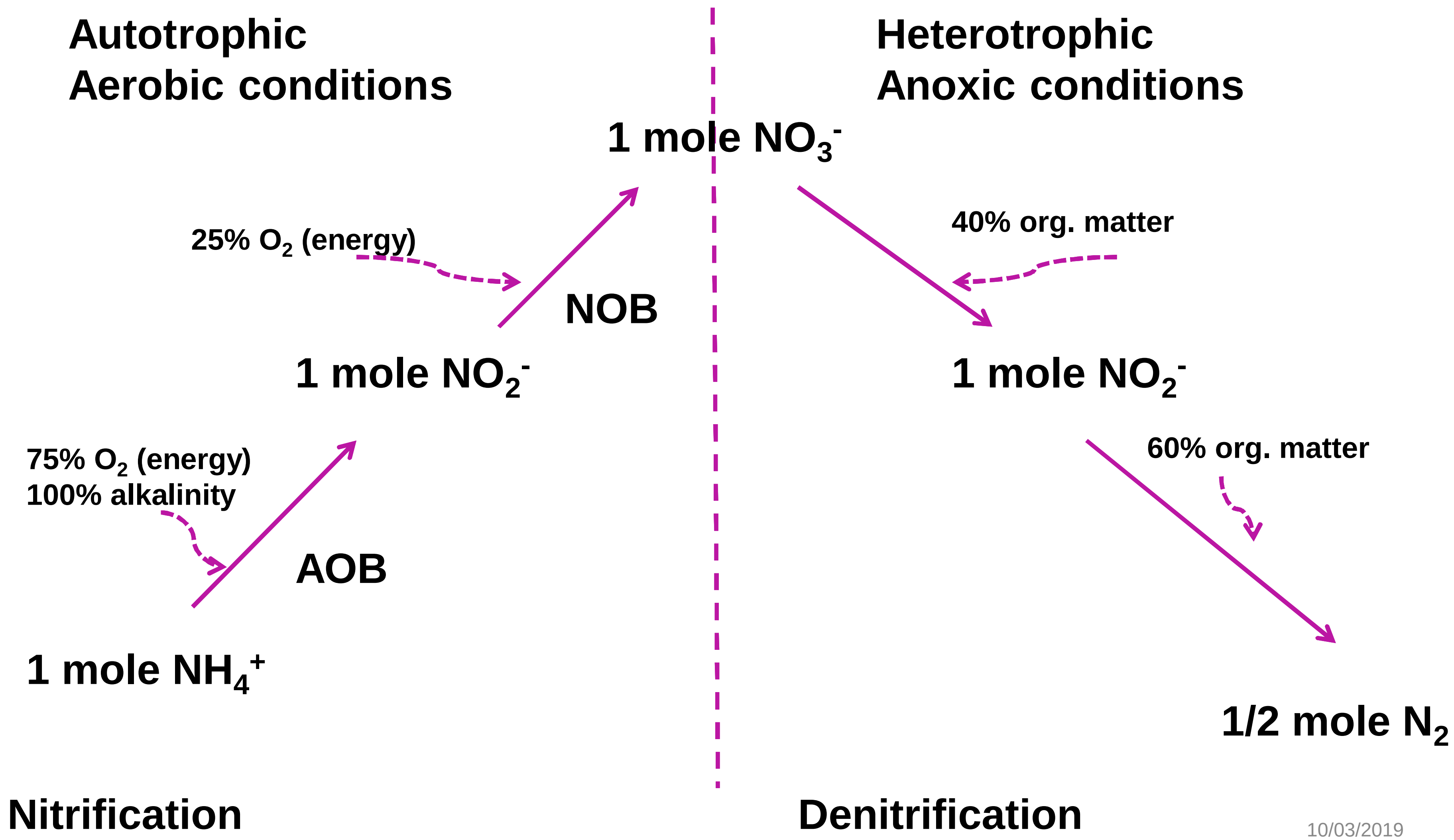
ND processes

- more energy
- carbon source addition
- more lime
- removal up to 95%
- easier to control
- more expensive

DN processes

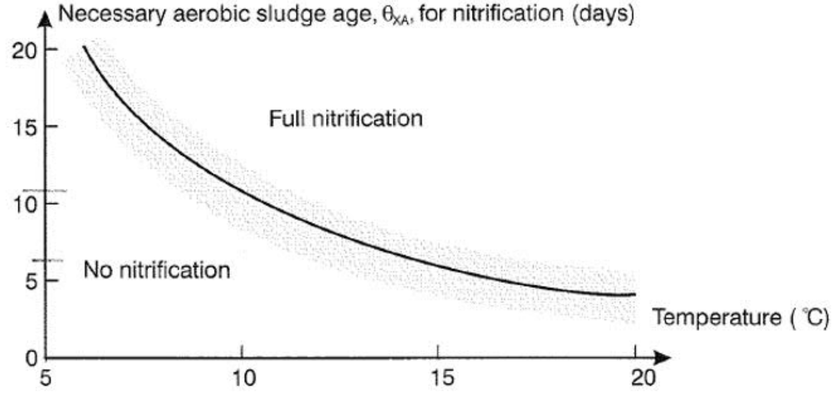
- some of the aeration compensated
- no carbon addition
- less lime
- removal depends on C/N-ratio and nitrate recycle - max. 70 - 80% (typically 65%) without carbon addition

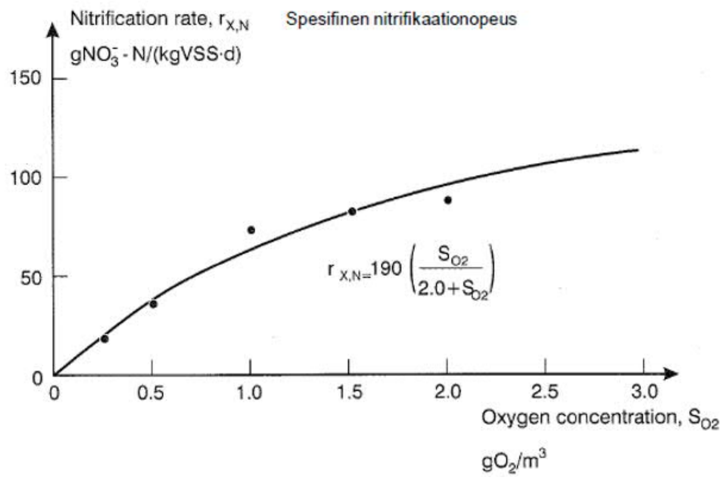
Conventional (N removal 1.0)

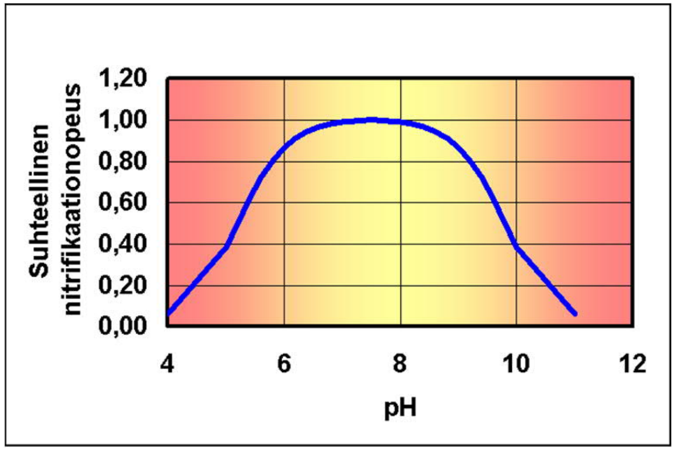


Dimensioning of the process for nitrification

- The limiting process
- Temperature
- DO
- pH
- Toxic substances







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.

Dimensioning of the anoxic volume (denitrification)

- **Wastewater quality**
  - Carbon to nitrogen ratio
  - Toxic substances
  - Readily biodegradable organic matter

- **Retention time minimum 0,5 – 2 h**
- **To be checked based on the carbon source**

Carbon source	g N / kgVSSh		
	7 °C	14 °C	20 °C
Raw WW	0,6	1,5	3
Primary settled WW	0,6	1,5	3
Pre-fermented WW	1-2	2-5	5-10
Acetic acid	2	5	10
Methanol	2	5	10

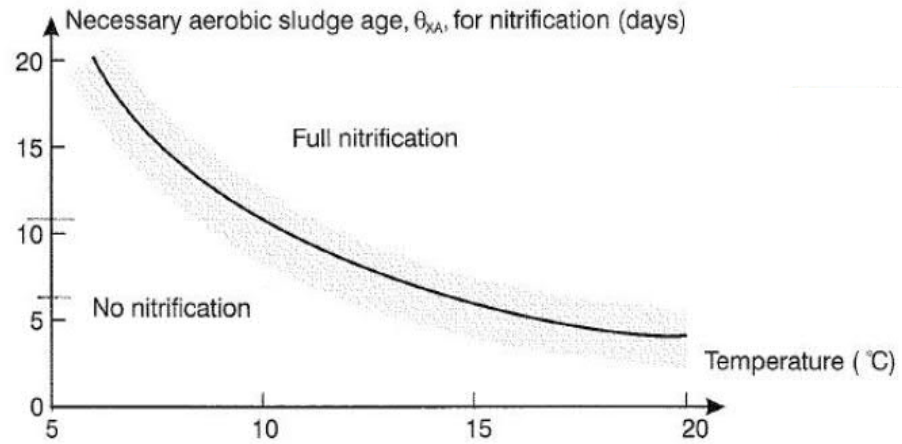
:

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 70% total nitrogen removal (nitrification + denitrification) is achieved using the data in the table.

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

DEMO 1

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

Assumption 1: No nitrate in the influent water

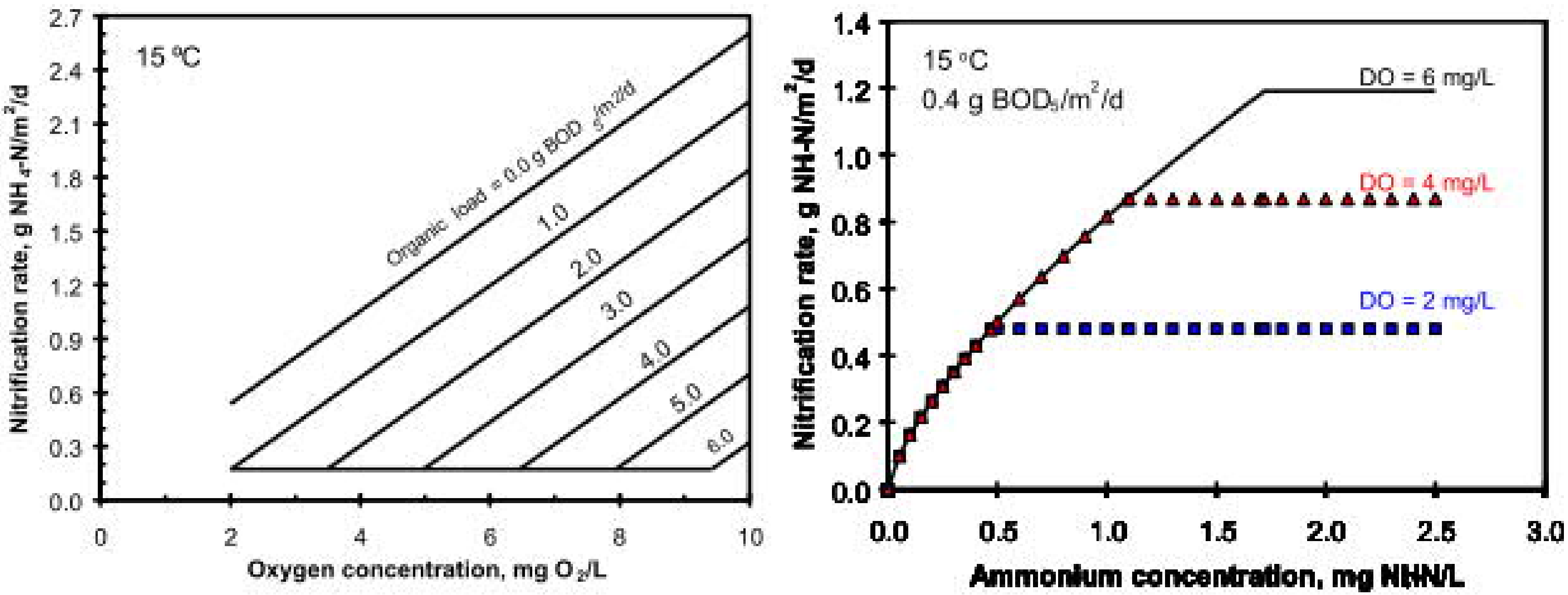
Assumption 2: No denitrification in the secondary clarifiers.

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

Nitrification in MBBR



- Kuvat: Odegaard 2014

Denitrification in MBBR

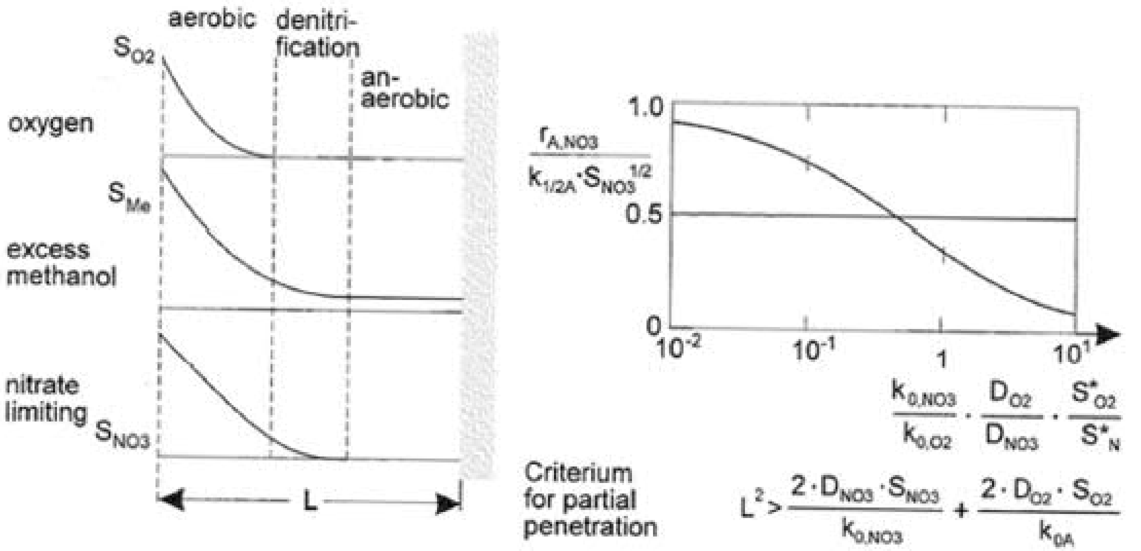


Figure 7.5. The figure shows how denitrification may occur in spite of aerobic conditions in the free water. Nitrate diffuses through the aerobic part of the biofilm and is denitrified in the anoxic zone. To the right the reduced denitrification rate is shown compared with denitrification without oxygen.

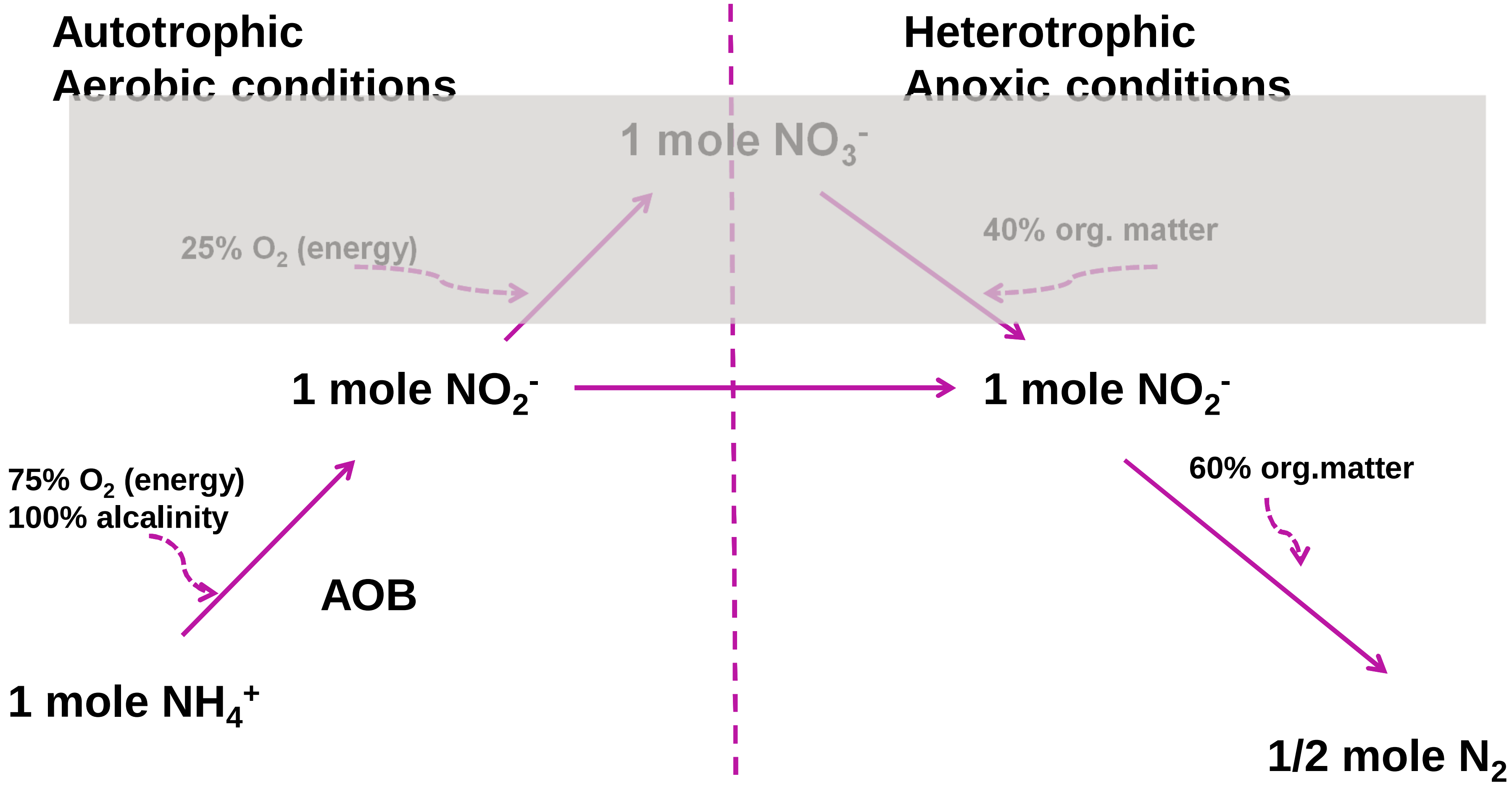
BACTERIA GAME – ADVANCED VERSION ☺

- Everybody gets 1-2 cards
- Cards contain bacteria, wastewater constituents, end-products of processes and oxygen
- Two zones are formed with right conditions and bacteria – aerobic and anoxic zones
- Wastewater (organic matter and ammonium) enters the process
- When a good combination for a reaction to take place is achieved, substrates are replaced by end-products
- Test different configurations

Short-cut nitrogen removal

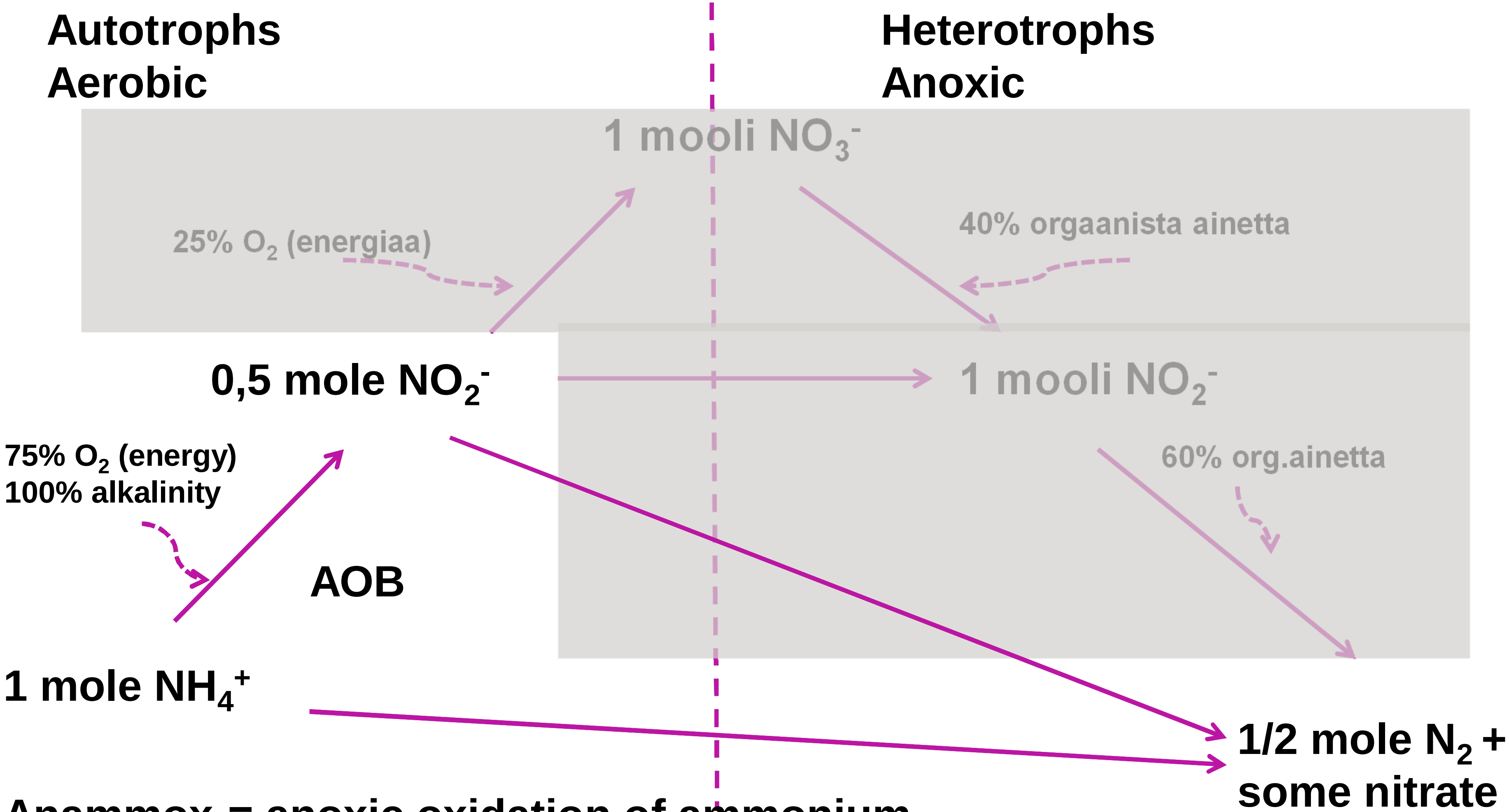
Aalto University
School of Engineering

Nitritation-denitritation (SND)
N removal 2.0



Less oxygen, less organic matter, less sludge

Nitritation – Anammox or Deammonification



Anammox = anoxic oxidation of ammonium
Anammox belong to Planctomycetes

Deammonification reaction

$$NH_4^+ + NO_2^- \rightarrow N_2 + 2\,H_2O\ (\Delta G° = -357\ \mathbf{kJ/mol})$$

The combination of partial nitritation and anammox is referred to as deammonification.

Due to the anabolic reaction, AMX growth is always associated with NO_3^- production, which is stoichiometrically 11 % of ammonium converted.

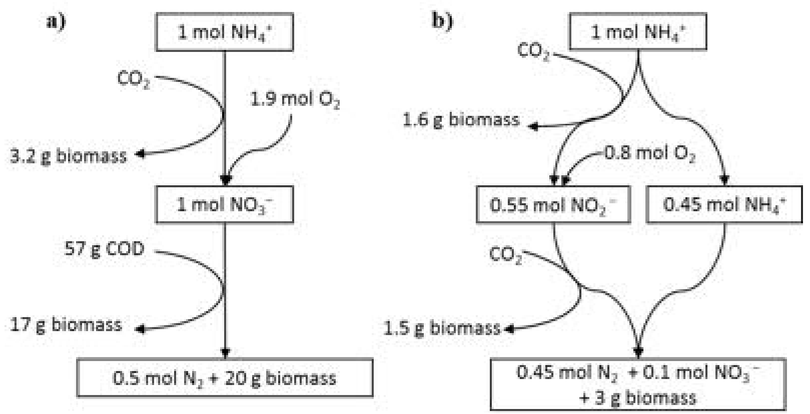


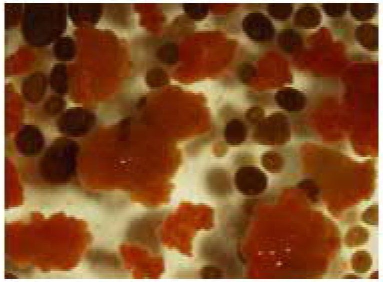
Figure 6. The carbon flows and oxygen demand of a) conventional nitrogen removal and b) deammonification (after Siegrist et al. 2008).

Vilpanen, 2017

Anammox bacteria

- Low Growth Rate
  - approx. 10 day doubling time at 30°C
  - <10 day has been reported (Park et. al - 5.3 - 8.9 days)
  - SRT (>30 days)

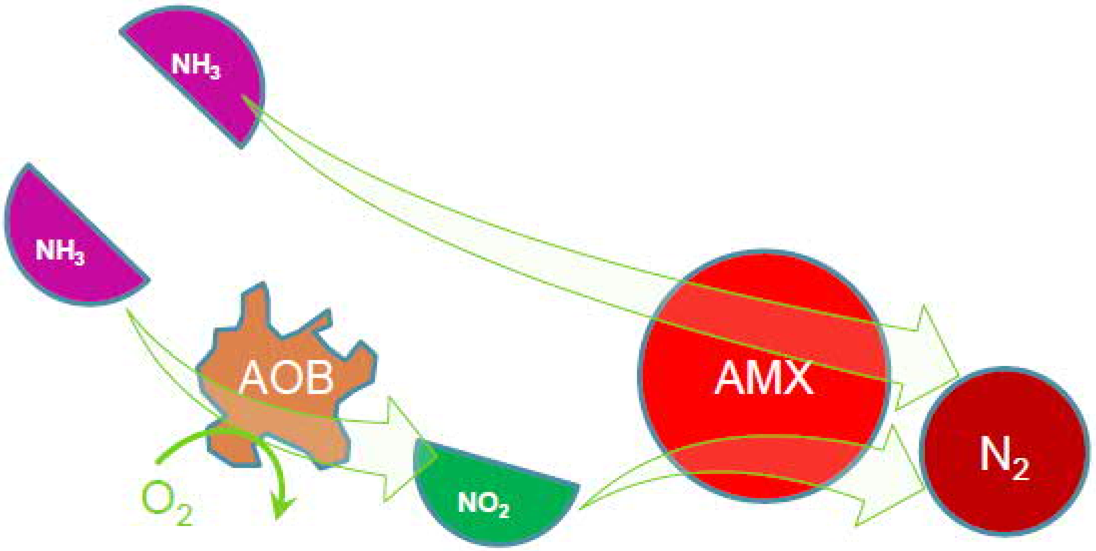
- Sensitive to;
  - Nitrite
    - Toxic- irreversible loss of activity based on concentration & exposure time
    - $NH_4^+ : NO_2^-$ ratio 1 : 1.32
  - DO - reversible inhibition
  - Free ammonia (<10 -15 mg/l)
  - Temperature >30°C preferred
  - pH (neutral range)



Source: AECOM 2012

Deammonification

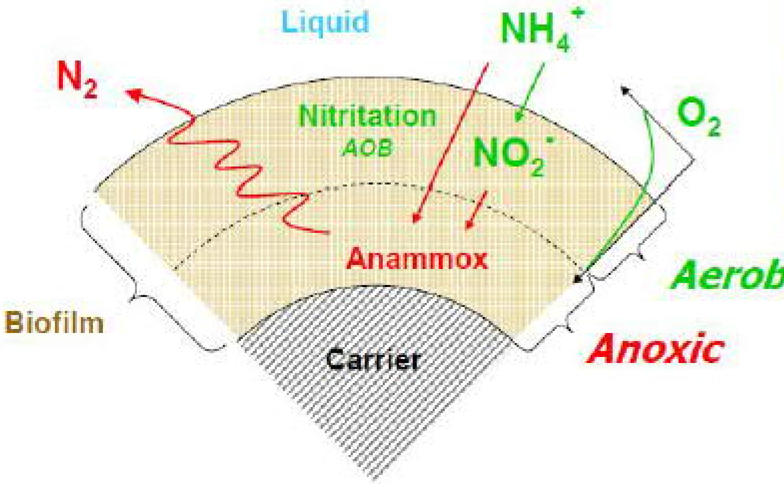
- Two-step process
  - Aerobic ammonia oxidation to nitrite (by AOB)
  - Anaerobic ammonia oxidation to nitrogen gas (by anammox)

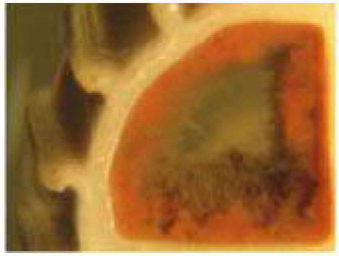


Deammonication processes

- OLAND (Oxygen Limited Autotrophic Nitrifacation Denitrification)
- CANON Completely Autotrophoic Nitrogen removal Over Nitrite
- DEMON® Suspended growth SBR
- AnitaMOX® Attached growth MBBR
- ANAMMOX® (Paques) Upflow granulation process

- Simultaneous aerobic and anaerobic conditions in biofilm layers
  - NH_3-N, alklainity & DO in the bulk liquid
  - AOBs on the outer aerobic layer
  - ANAMMOX on the inner anaerobic layer



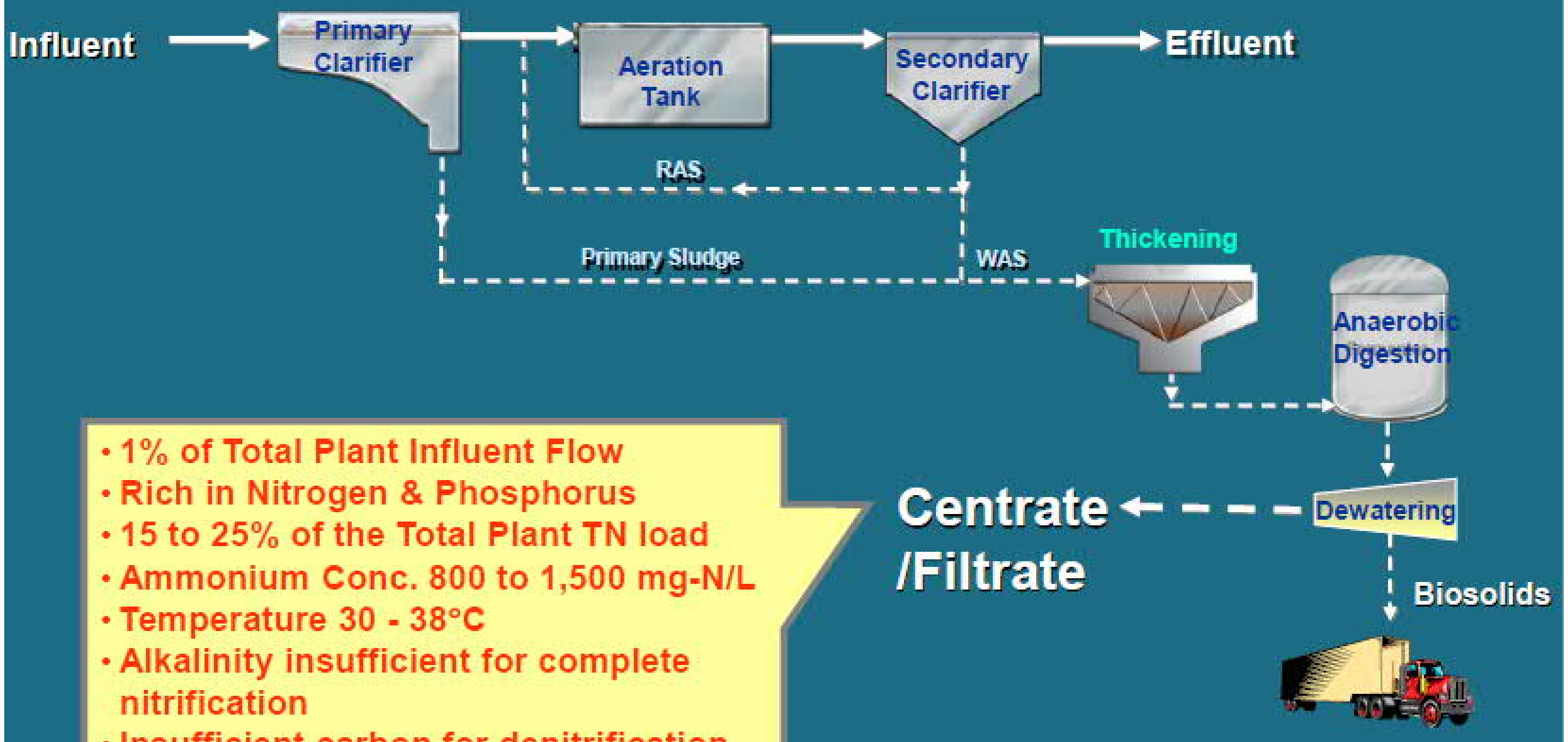


Courtesy Veolia

- ANAMMOX organisms in attached growth are less sensitive to inhibitory compounds
  - DO: 3 mg/L vs. 0.3 mg/L suspended
  - NO_2-N: 50 mg/L vs. 5 mg/L suspended

Source: AECOM 2012

Centrate treatment



- 1% of Total Plant Influent Flow
- Rich in Nitrogen & Phosphorus
- 15 to 25% of the Total Plant TN load
- Ammonium Conc. 800 to 1,500 mg-N/L
- Temperature 30 - 38°C
- Alkalinity insufficient for complete nitrification
- Insufficient carbon for denitrification
- For a Bio-P plant with no iron addition:
  - Centrate TP = 200-800 mg/L

Source: AECOM 2012

Deammonification in Finland

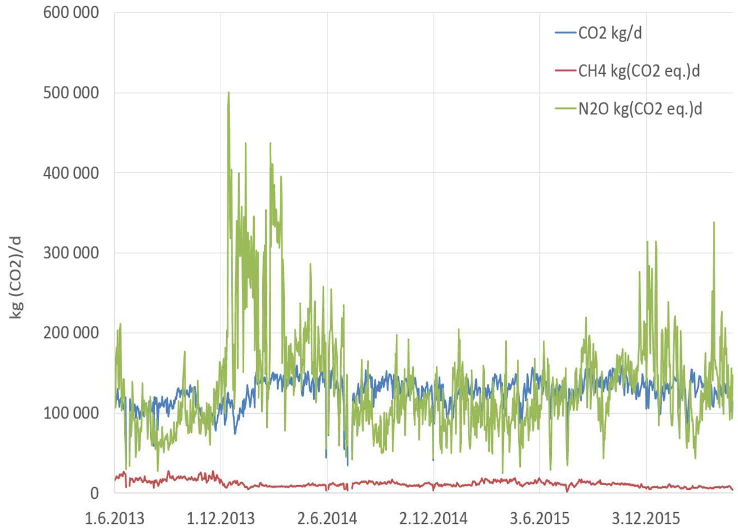
- Lakeuden Etapin puhdistamo (reject water of a biogas plant
- A couple of other smaller reject water treatment processes
- Large-scale piloting at Viikinmäki HSY since 2015

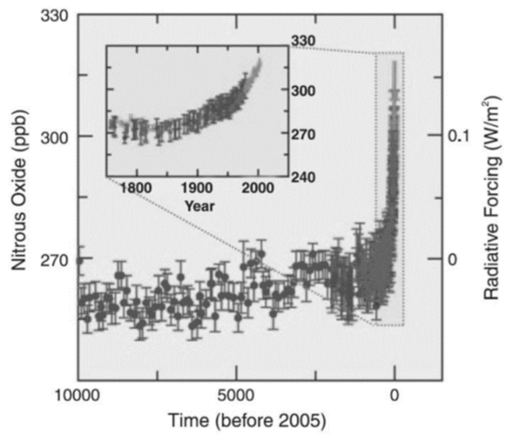
N_2O and wastewater treatment

300 times stronger greenhouse gas compared to CO_2

Produced in the biological nitrogen removal

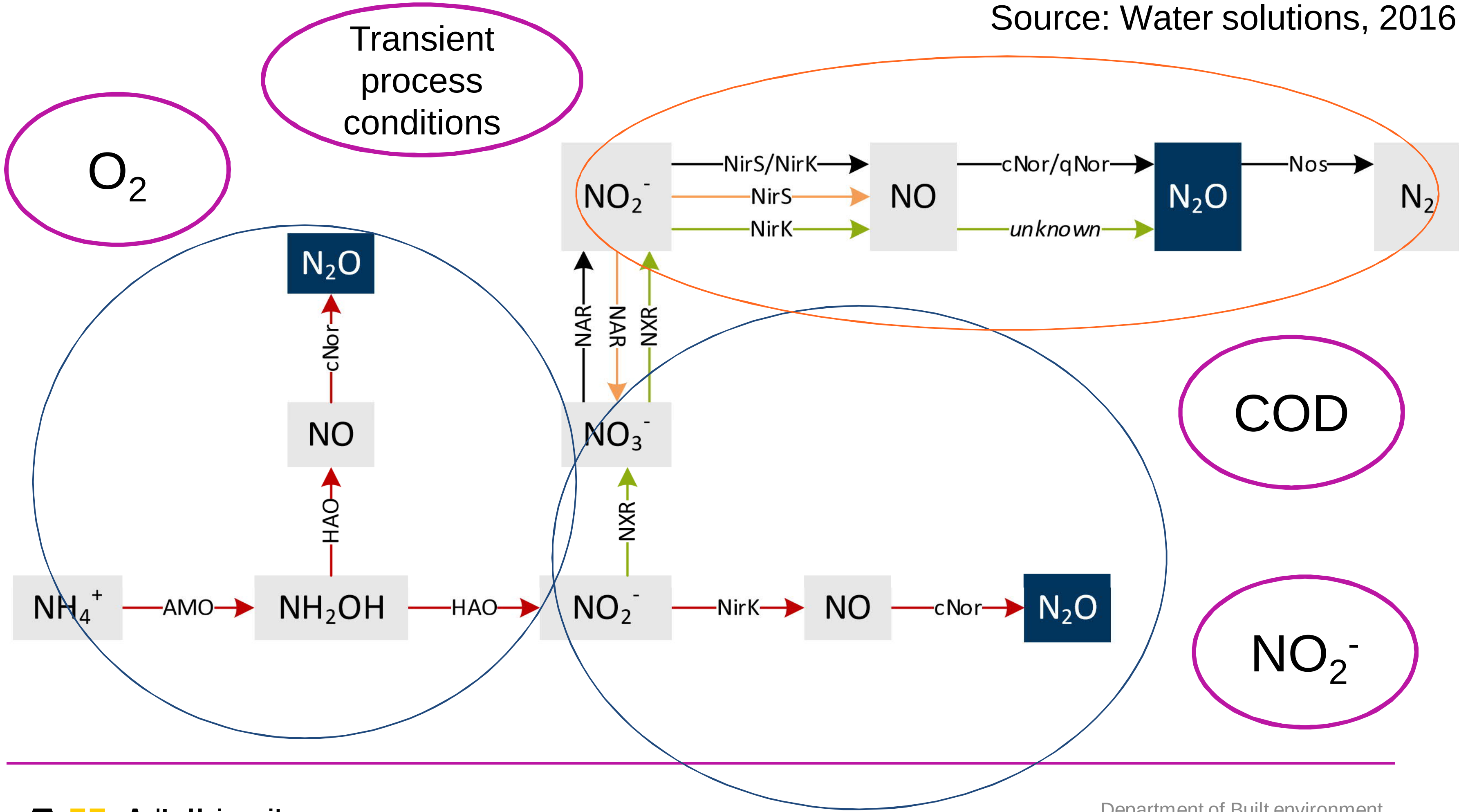
Often the most significant greenhouse gas emitted in wastewater treatment





Production of N_2O in the wastewater treatment

Source: Water solutions, 2016



Reading material

Biological wastewater treatment (Course book):

Chapters

2.4.2

4.11

4.2-4.3

4.11

Nitrogen removal

5.1

6.1

6.3-6.4

6.5

Activated sludge process from the other course book (Environmental Biotechnology)

Pages 213-222

Biofilms (Biological WWT)

Chapters:

17.1.

18.1-18.2

18.4