ENV-405 Session 2
Wastewater treatment
Lecture 4 Nov 25

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Slides acknowledgment: Christof Holiger

Questions from last lecture:

- Why do we nitrify fully but denitrify partially?

Compound	Formula	Relative Toxicity	Primary Mechanism of Harm	Typical Toxic Range (as N)
Unionized Ammonia	NH_3	**Most Toxic**	Direct neurotoxicity and gill damage	0.01-0.05 mg/L
Nitrite		**Intermediate**	Methemoglobinemia (internal suffocation)	0.5-5 mg/L
Nitrate		**Least Toxic**	Eutrophication; very high dose methemoglobinemia	100-400 mg/L

- Why sometimes (homework) treat TKN and ammonia interchangably? (looking from the oxidative state point of view)
- Added 2 missing details in HW2.
- See the score for Midterm 1?

Today’s content:

- Design of attached growth bioreactor:

biotrickling filters and biological contactors

- Design of hybrid system:

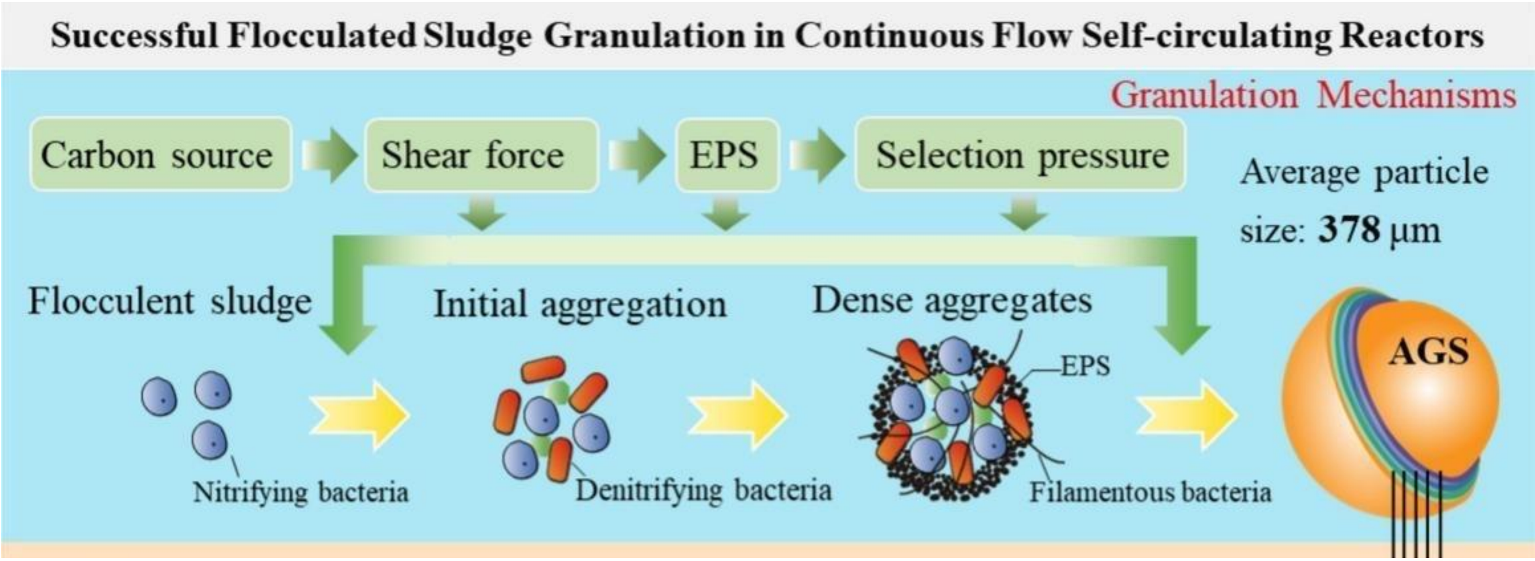
moving bed biological reactors

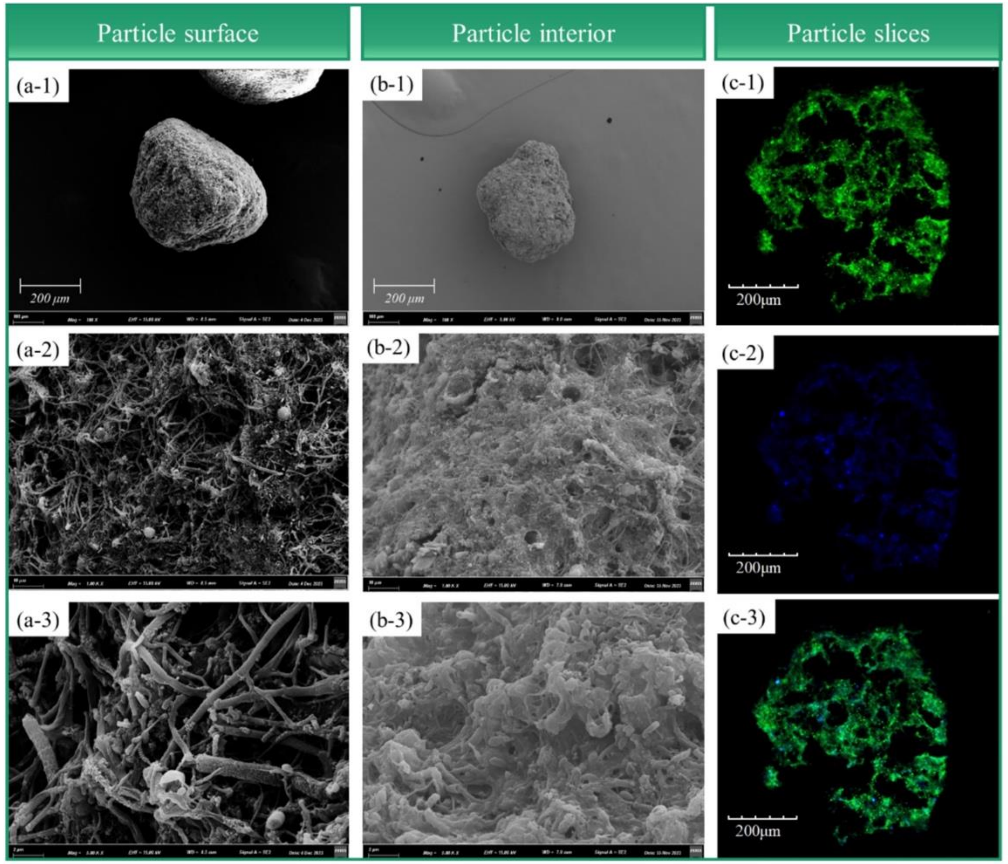
Theory of attached growth: building upon the sptial arrangement of activated sludge granules!

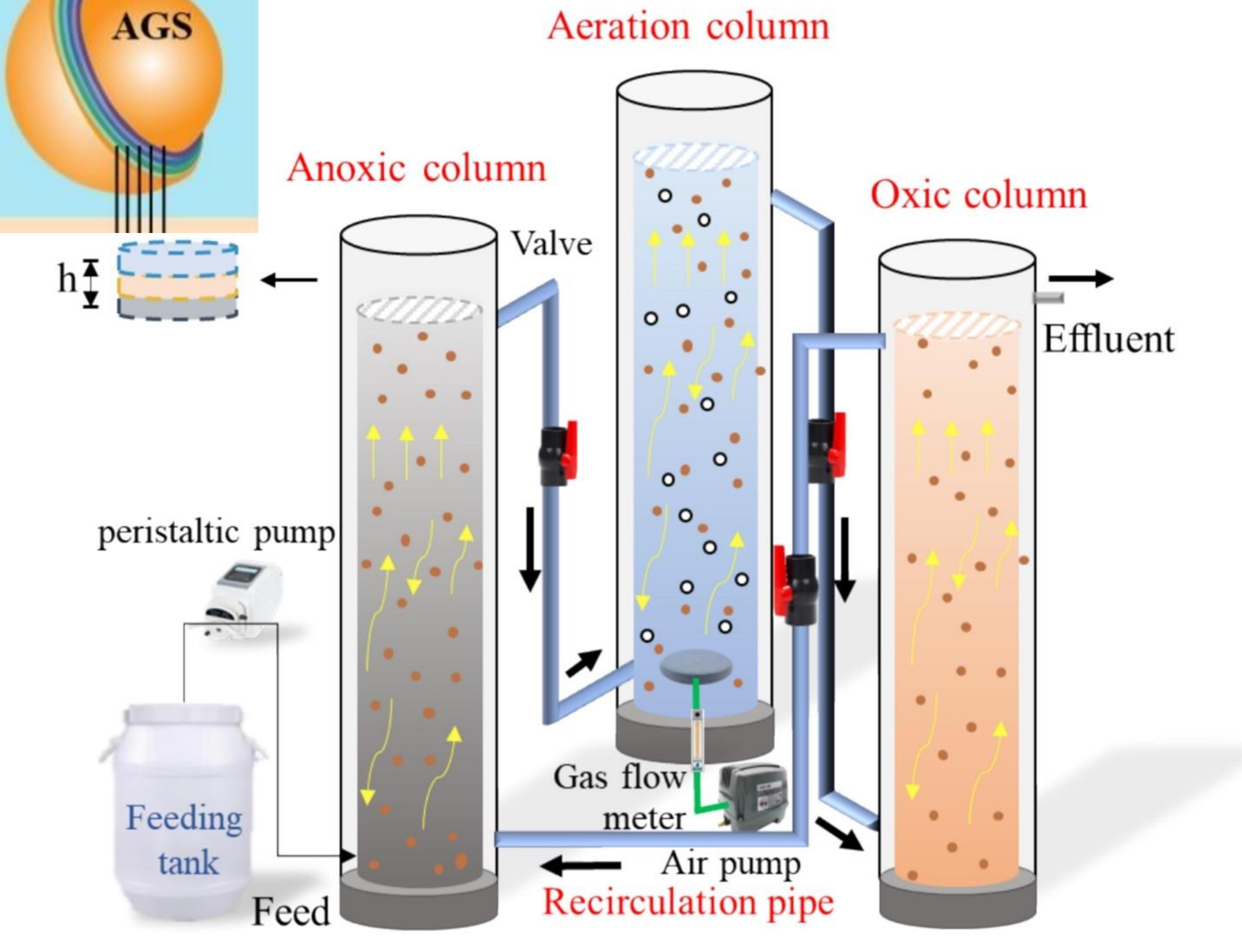
- These terms take advantage of self-spatial arrangement of microorganisms communities: advanced forms of Activated Sludge include AGS (Aerobic Granular Sludge) and DAS (Densified Activated Sludge), for better settling.

Feature	**Conventional Activated Sludge (CAS)**	**AGS and DAS (Advanced AS)**
Biomass Form	**Flocs** (Low density, irregular, <0.2 mm)	**Granules** or **Dense Flocs** (High density, spherical, > = 0.2mm)
Separation	Slow settling, **Requires a large secondary clarifier**	Very fast settling, Secondary clarifier is possibly omitted
Process Mechanism	Homogenous mix; aerobic/anoxic conditions are typically separated in different tanks.	**Stratified/Layered Biomass**; multiple redox zones occur inside the single particle.
Selective Pressure	Low	**High** (e.g., very short settling time, specific feeding regimes)

Stability issue, rampup time is long







https://www.sciencedirect.com/science/article/pii/S1385894725039452#f0005

The Biofilm

- Complex assembly of microbial community in a matrix of extracellular polymeric substances
- Grows attached to a support material
- Can range in thickness from several microns to several mm depending on the availability of substrate and nutrients
- Biofilm cells different from planktonic cells

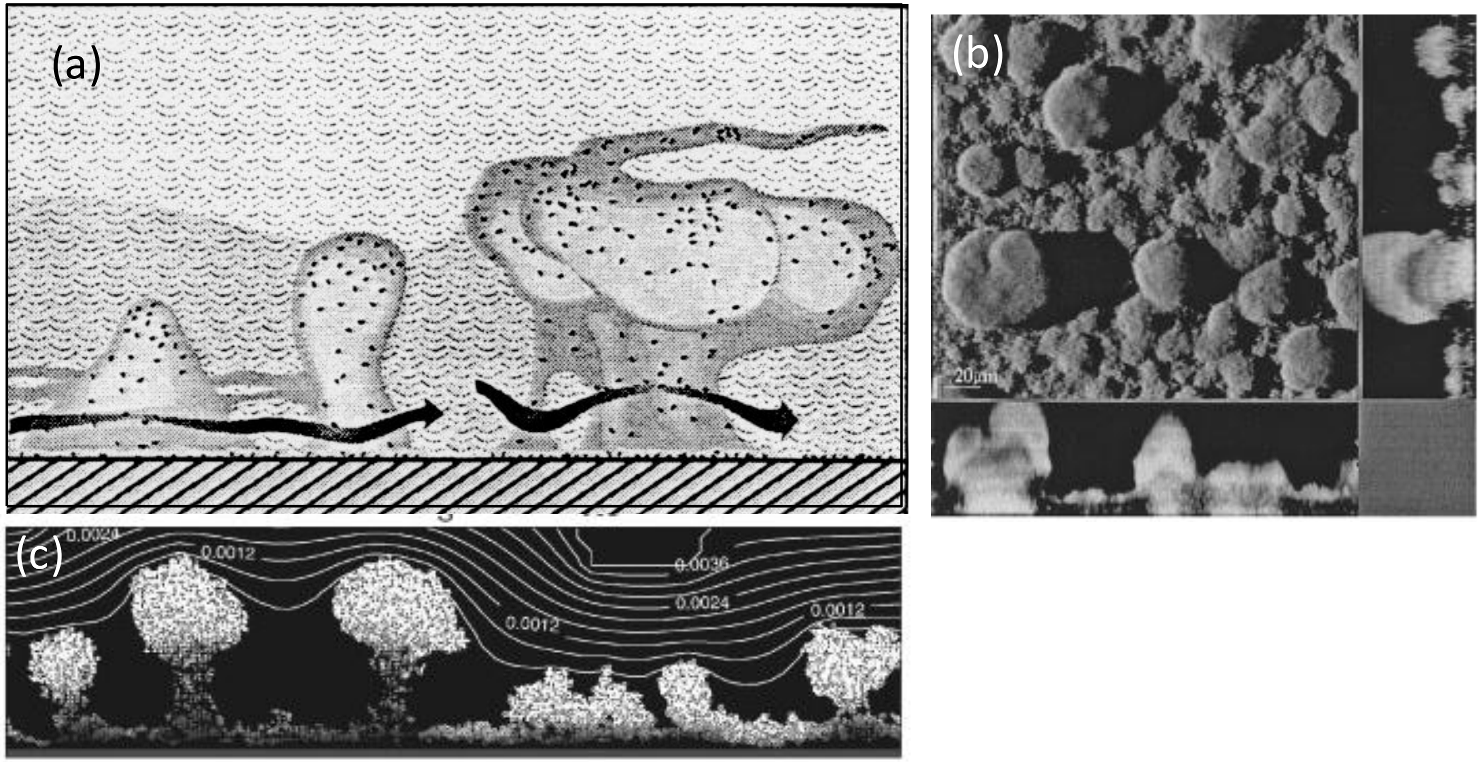
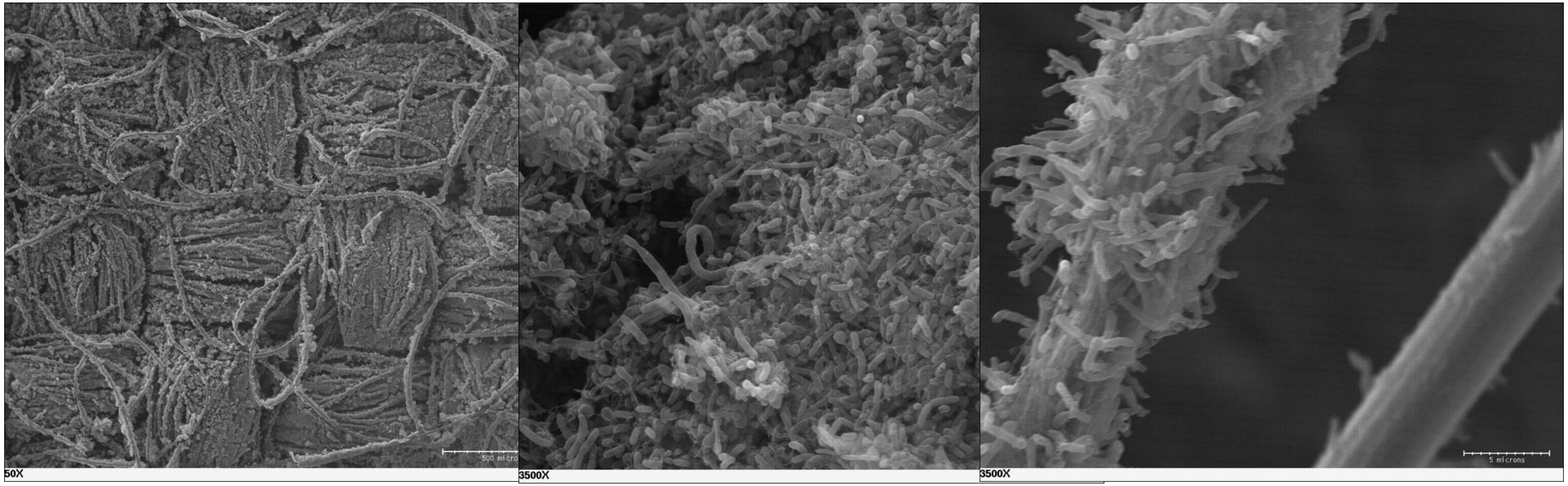
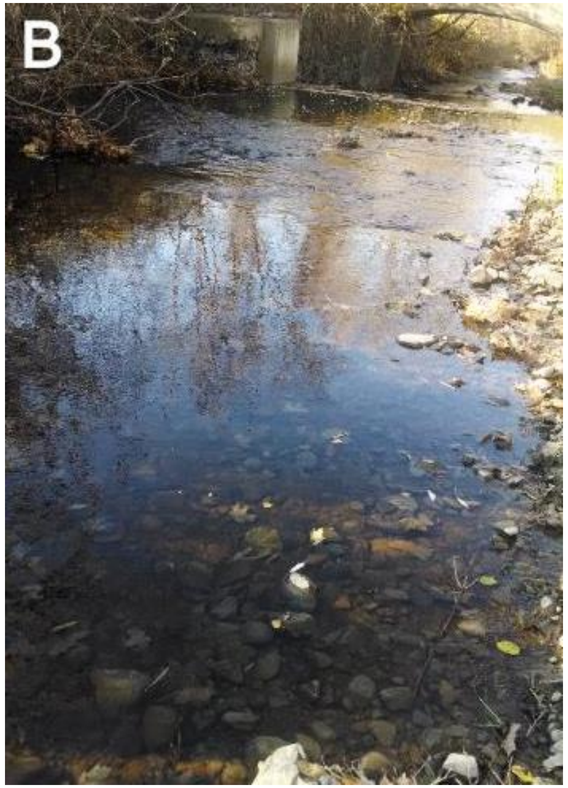


Figure 16.3 Architecture of a biofilm: (a) Artist's conceptualization of the architecture of a biofilm; (b) Confocal laser scanning micrograph of a *Pseudomonas aeruginosa* biofilm; and (c) Two dimensional biofilm architecture generated using a mathematical model describing the growth of a heterotrophic organism that generates extracellular polymeric substances


500 micro
50X
3500X
5 microns
3500X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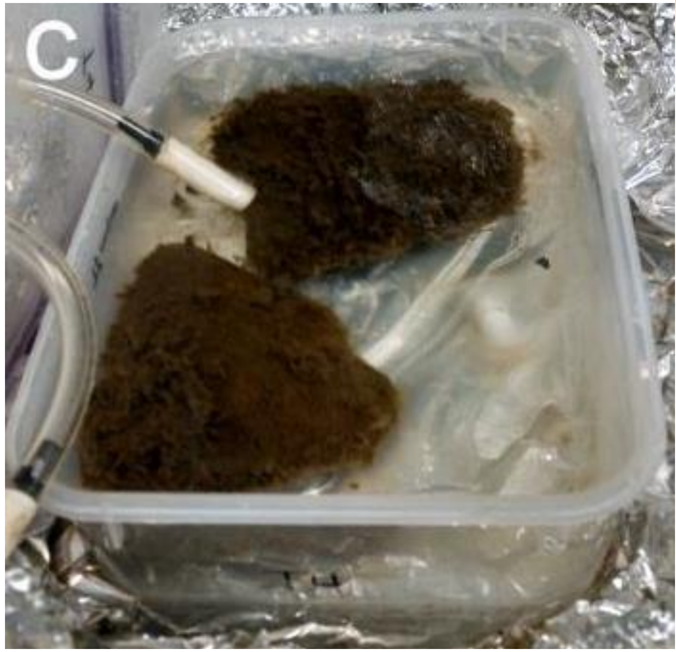
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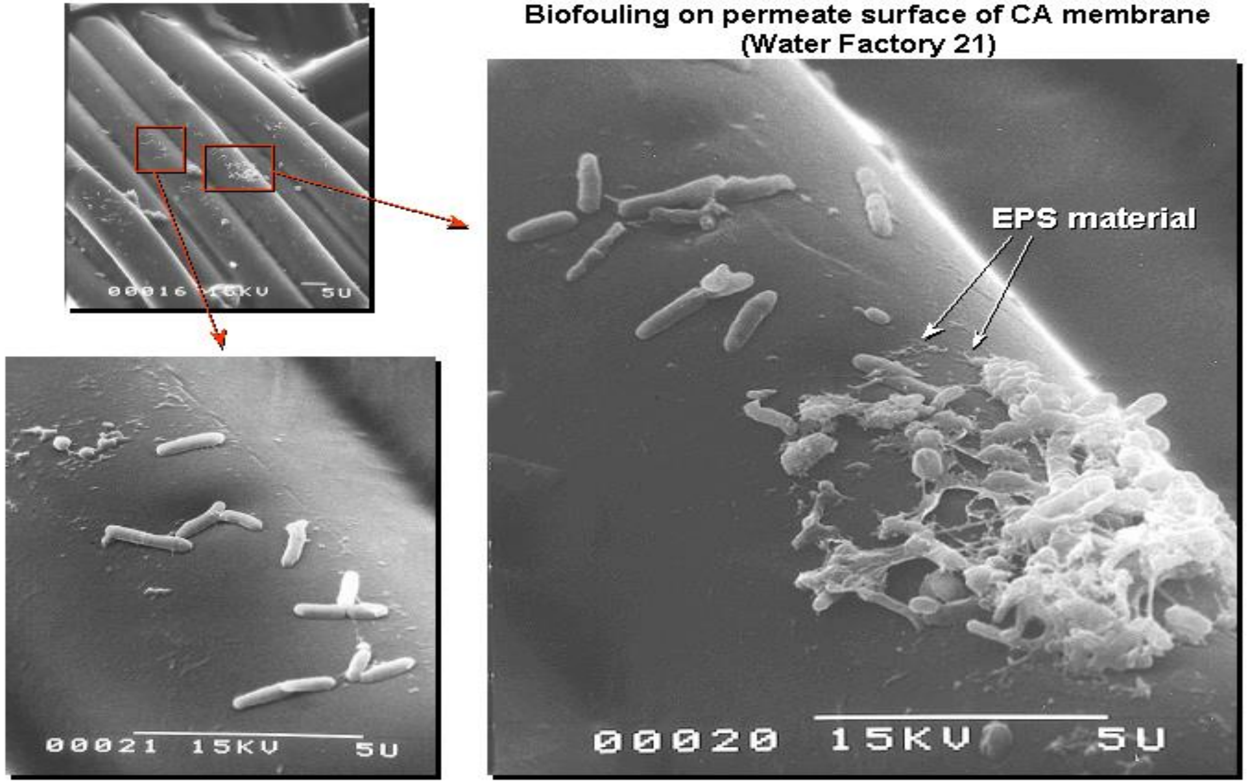
Biofilms in Environmental Biotechnology

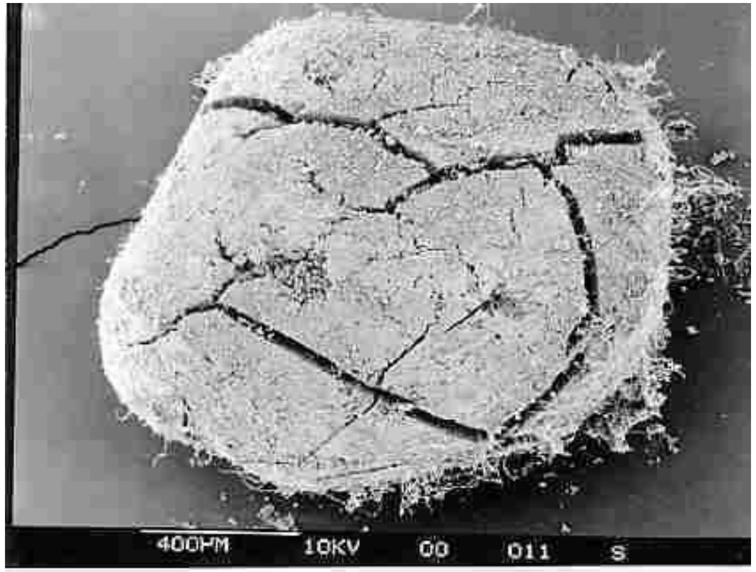
- Detrimental biofilms
  - Membrane fouling
  - Drinking water distribution systems
  - Heat exchangers



Biofouling on permeate surface of CA membrane
(Water Factory 21)

Biofilms in Environmental Biotechnology

- Beneficial biofilms
    - Wastewater treatment
    - Drinking water treatment
    - Bioremediation of soil, groundwater
    - Barriers to contain contaminant plumes in subsurface
    - Gas/air treatment



SEM_SandGrainCrackedBiofilm.jpg
(Mike Dempsey)

Attached growth reactor

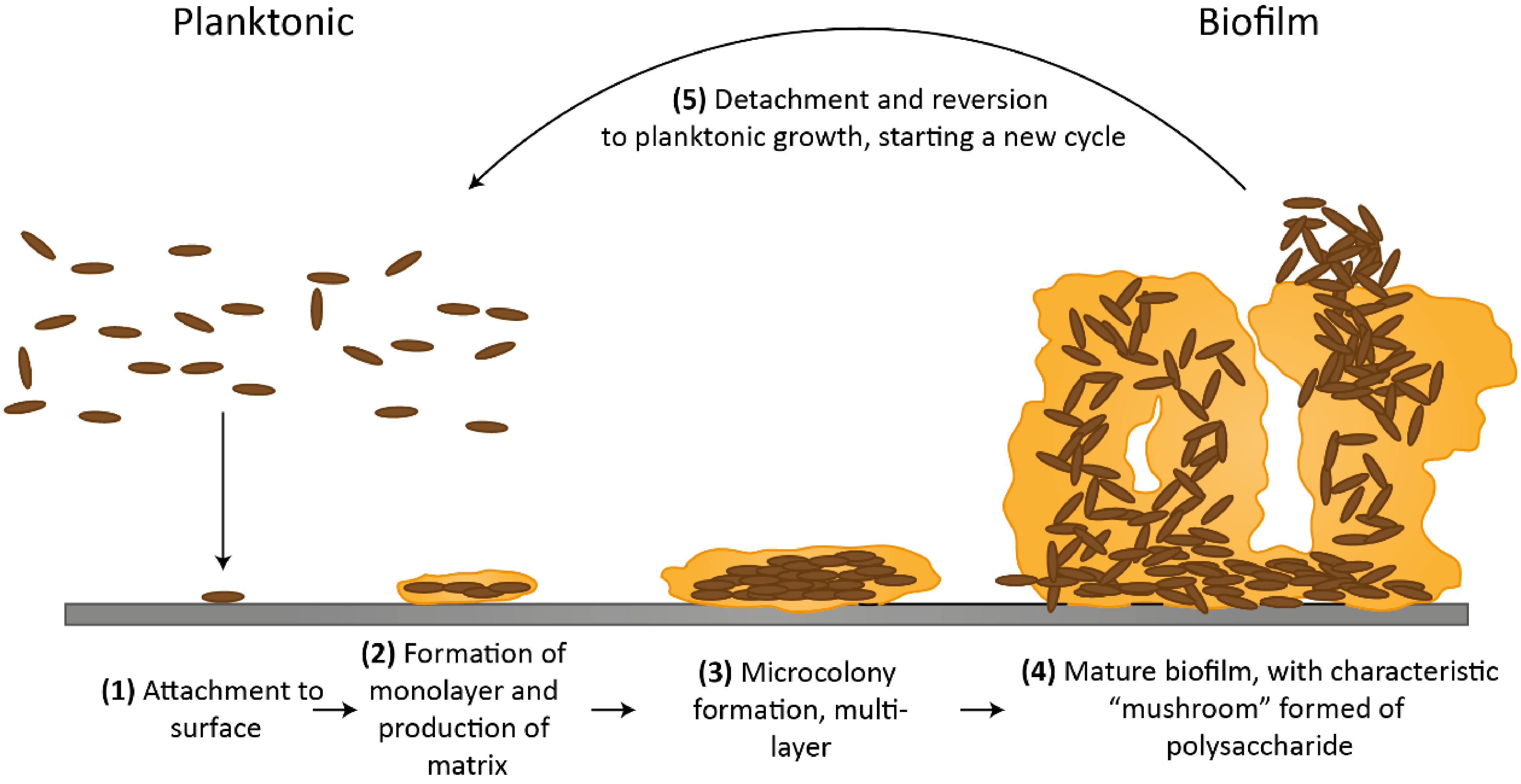
- Utilize biofilm growing on an impermeable surface
  - Suspended carrier & granule
  - Immobile carrier

→ High biomass concentration

→ Efficient retention of biomass

→ Resistant to environmental stress

Modeling attached growth systems



Planktonic

Biofilm

(5) Detachment and reversion to planktonic growth, starting a new cycle

(1) Attachment to surface →

(2) Formation of monolayer and production of matrix →

(3) Microcolony formation, multi-layer →

(4) Mature biofilm, with characteristic "mushroom" formed of polysaccharide

Conventional Biofilm Conceptualization

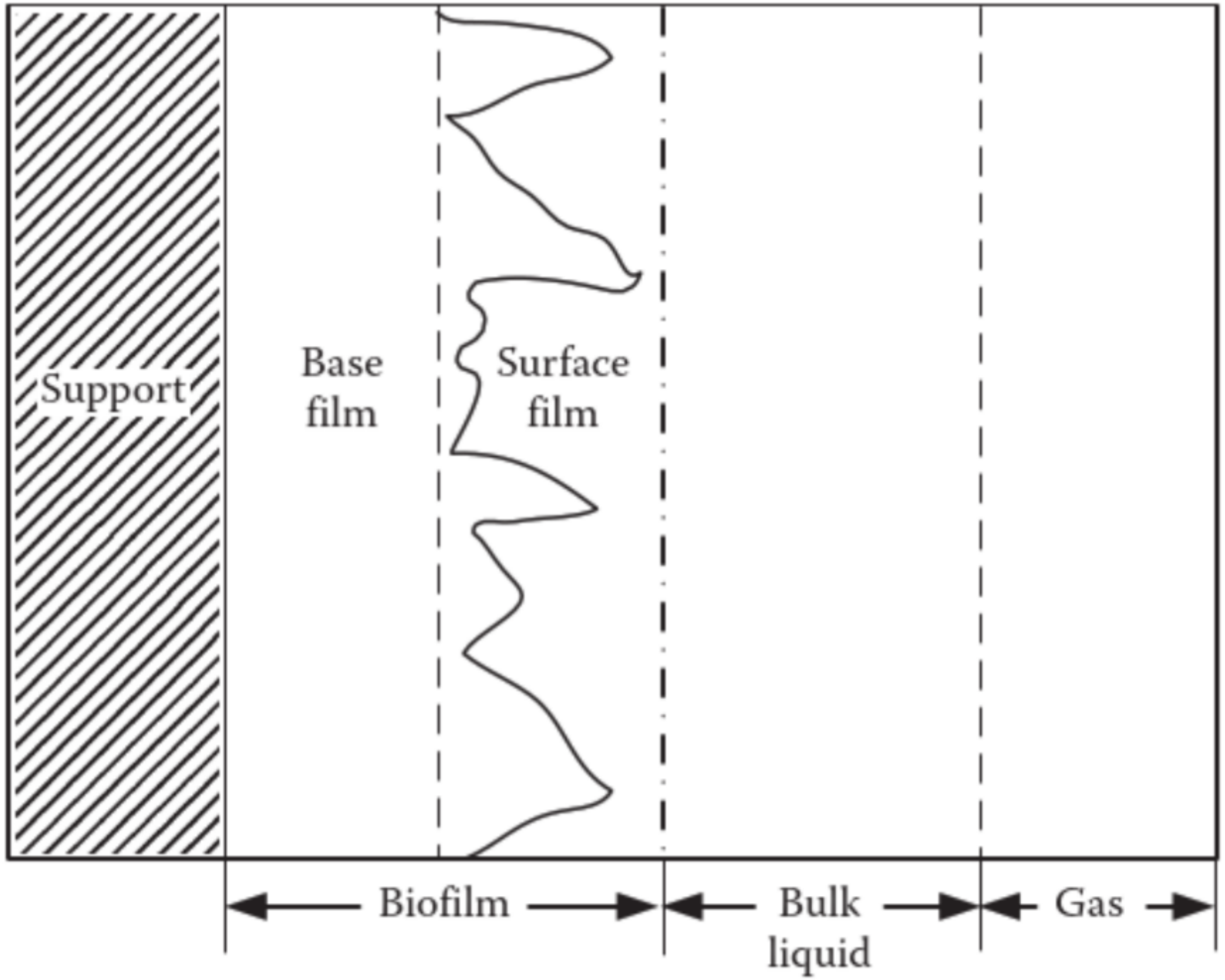


Figure 16.1 Conceptualization of a biofilm system

Traditional Conceptual Model of Soluble Concentrations in Biofilm

- One species biofilm with one substrate with a bulk solution concentration of S_{Sb}
- Substrate moves into the biofilm by diffusion
- Substrate concentration gradient
  - It decreases linearly in the boundary layer as there is no reaction, just diffusion.
  - As it reaches the biofilm, it starts to get consumed and decreases to zero as it reaches the substratum

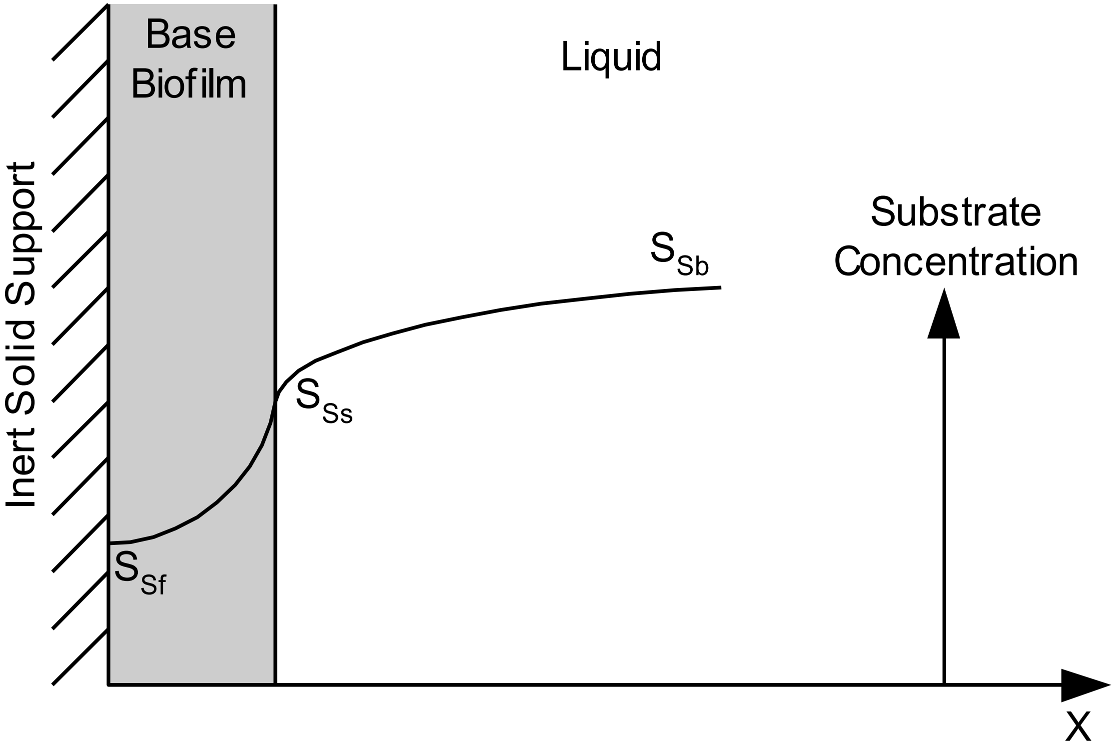


Figure 16.4 Traditional conceptualization of a base biofilm showing a typical concentration profile for a single limiting nutrient.

Traditional Conceptual Model of Soluble Concentrations in Biofilm

- Bacteria near the liquid-biofilm interface grow faster than those deeper within the biofilm.
- As interior bacteria grow, they occupy more space, displacing cells near the boundary further away from substratum.
- Biomass decay leads to debris accumulation
- As particles move outward from the inner regions, they are removed by surface shear force

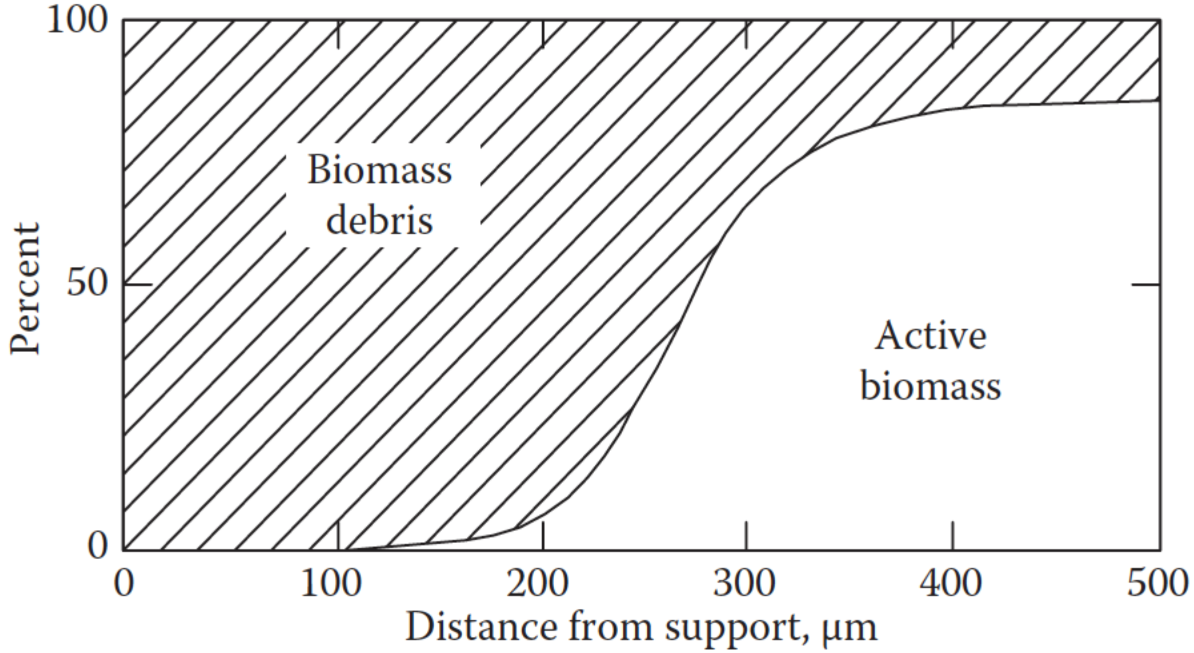


Figure 16.5 Simulation results showing the relative distribution of active biomass and biomass debris.

Mass transfer to and within a biofilm

- Separate transport phenomena:
  - from bulk liquid to biofilm surface by molecular diffusion, advection and dispersion (external mass transfer)
  - from biofilm surface into biofilm by molecular diffusion and advection (internal mass transfer)

- Observed substrate consumption rate depends upon
  - rate of mass transport (external and internal)
  - substrate consumption rate at various S_{sf}

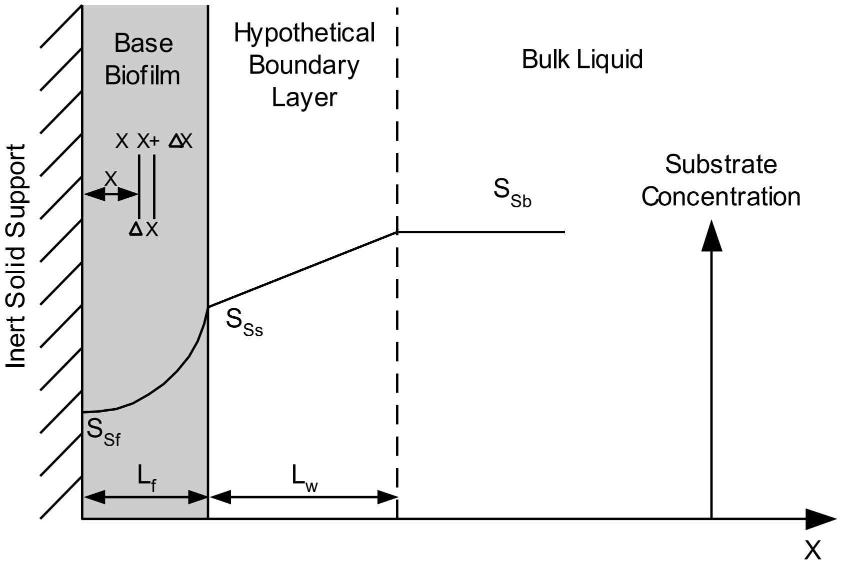


Figure 16.7 Traditional conceptualization of a base biofilm showing an idealized concentration profile for a single limiting nutrient.

Use of biotrickling filters and contactors

- These attached-growth systems are traditionally aerobic systems, so they are excellent for:

Carbon oxidation (BOD removal)

Nitrification ($NH_4^+ \rightarrow NO_3^-$)

- They are not naturally suited for denitrification, because:

The process requires anoxic conditions (no oxygen).

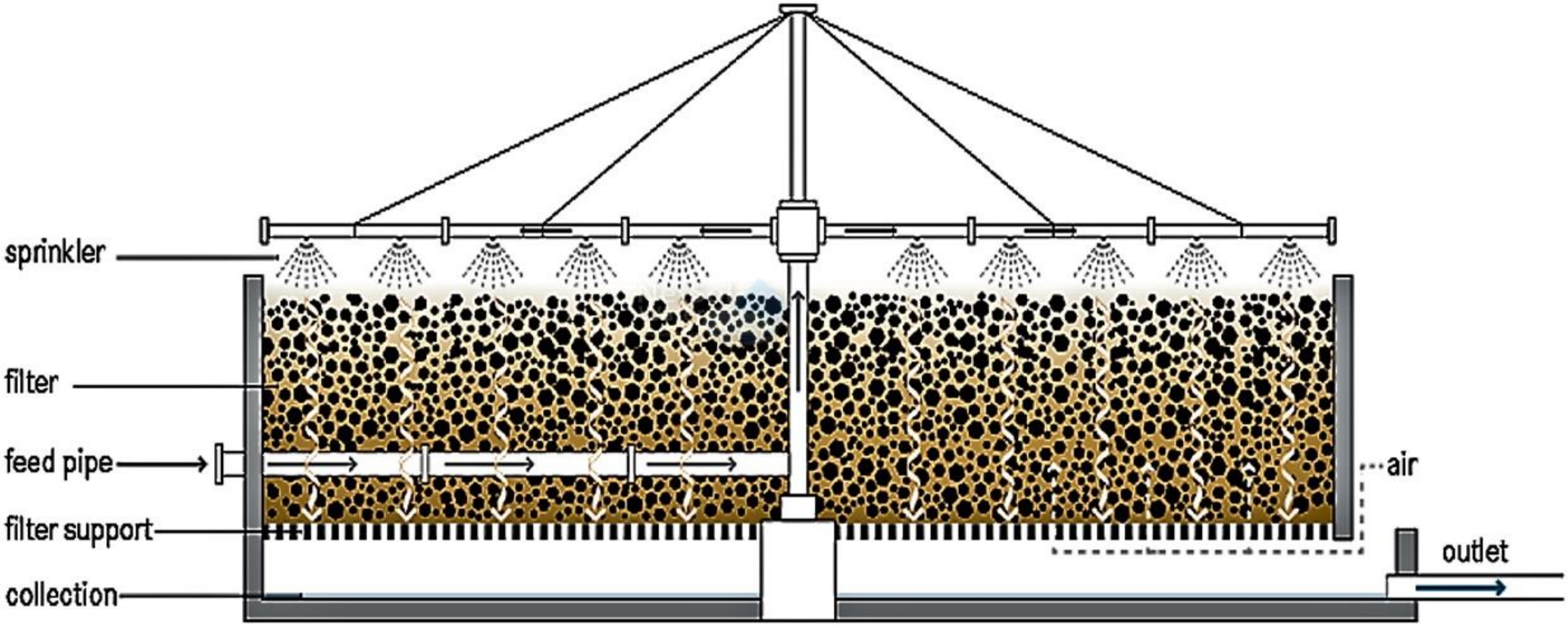
Trickling filters and RBCs are typically well-aerated (natural or forced).

If a plant already has trickling filters or RBCs, engineers sometimes estimate their potential for partial denitrification or simultaneous nitrification–denitrification (SND), especially:

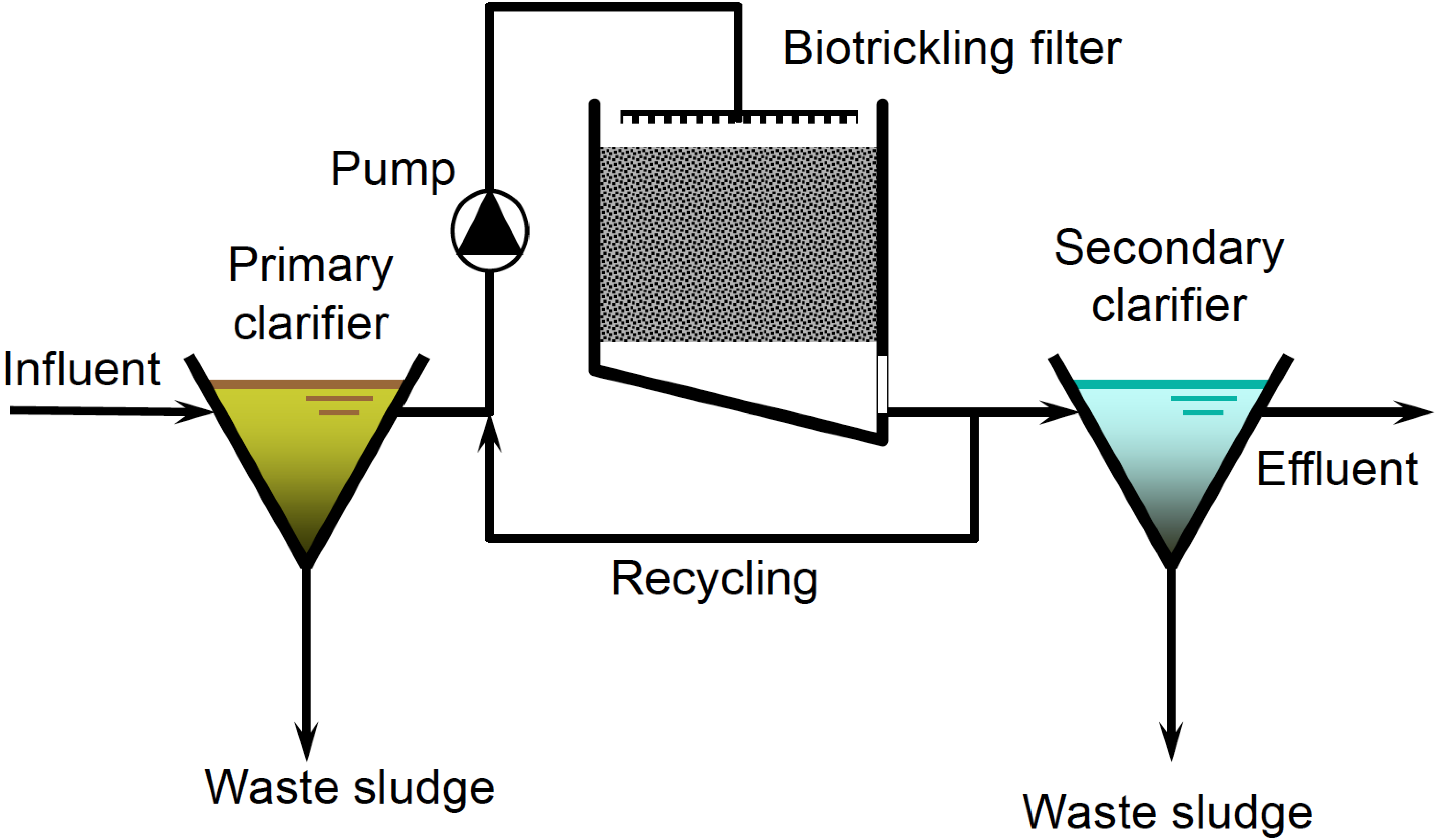
- If there are oxygen gradients in thick biofilms.
- Or if aeration can be limited in a retrofit.

This can yield partial nitrogen removal, but rarely full denitrification.

Biotrickling filters



Biotrickling filters


Biotrickling filter
Pump
Primary
clarifier
Secondary
clarifier
Influent
Effluent
Recycling
Waste sludge
Waste sludge

(Bio)trickling filters filled with rocks

$$B_v = \frac{Q_0 \bullet C_{0,BOD}}{V_{TF}}$$

B_v = volumetric load in g BOD_5 m^{-3} d^{-1}
Q_0 = influent flow rate in m^3 d^{-1}
$C_{0,BOD}$ = concentration of BOD_5 in influent in g m^{-3}
V_{TF} = volume of (bio)trickling filter in m^3

Typical values:
B_v = 400 g BOD_5 m^{-3} d^{-1} for elimination of BOD_5
= 200 g BOD_5 m^{-3} d^{-1} with nitrification included

(Bio)trickling filters filled with plastic packing material

$$B_A = \frac{Q_0 \bullet C_{0,BOD}}{a \bullet V_{TF}}$$

B_A = surface load in g BOD_5 m^{-2} d^{-1}

Q_0 = influent flow rate in m^3 d^{-1}

$C_{0,BOD}$ = concentration of BOD_5 of influent in g m^{-3}

a = colonisation surface per volume of filter in m^2 m^{-3}

V_{TF} = volume of (bio)trickling filter in m^3

Typical values:

B_A = 4 g BOD_5 m^{-2} d^{-1} for elimination of BOD_5

= 2 g BOD_5 m^{-2} d^{-1} with nitrification included

Dimensioning of a nitrifying trickling filter

$Q_0 = 3500\ m^3/d$
$C_{0,BOD} = 130\ g\ BOD_5/m^3$
$a = 140\ m^2/m^3$ (for plastic packing material)

nitrification

	without	with
Rock packing filter		
$V_{TF} = \frac{Q_0 \times C_{0,BOD}}{B_V} = \frac{3500\times130}{400(200)} =$	$1140m^3$	$2280m^3$
Plastic packing filter		
$V_{TF} = \frac{Q_0 \cdot C_{0,BOD}}{B_A \cdot a} = \frac{3500\cdot130}{4(2)\cdot140} =$	$815m^3$	$1630m^3$

More surface area available from commercialized plastic material than rocks.

We can also calculate dimension of a nitrifying trickling filter with specific surface loads

$$A_{tot} = A_{BOD_5} + A_{nit} = \frac{Q_0 \cdot C_{0,BOD_5}}{j_{BOD_5}} + \frac{Q_0 \cdot \left(C_{0,NH_4} - C_{e,NH_4}\right)}{j_{NH_4}}$$

A (area) is the **required surface area of the trickling filter** in m^2

Elimination rates at 10°C

$j_{BOD5} = 4 - 7\ g_{BOD5}\ m^{-2}\ d^{-1}$

$j_{NH4} = 0.9\ g_{NH4}\ m^{-2}\ d^{-1}$

Dimensioning of a nitrifying trickling filter with specific surface loads

$$A_{tot} = A_{BOD_5} + A_{nit} = \frac{Q_0 \cdot C_{0,BOD_5}}{j_{BOD_5}} + \frac{Q_0 \cdot \left(C_{0,NH_4} - C_{e,NH_4}\right)}{j_{NH_4}}$$

$$V_{TF} = A_{tot} / a_S$$

a_S (rock filter) = 80-100 m^2/m^3
a_S (plastic filter) = 90-220 m^2/m^3

Designing parallel reactors is helpful for maintenance events.

Final dimensions : height and diameter

- height limits: - rock packing filter 3-4 m
  - plastic packing filter 6 m
- diameter: $d = 2\sqrt{\frac{V_{TF}}{H \cdot \pi}}$

The height limits ensure sufficient **aeration**, **hydraulic performance**, and **structural safety** — deeper filters risk clogging and anaerobic conditions for rock media, but plastic media can handle taller designs thanks to their light weight and open structure.

Dimensioning of a nitrifying trickling filter

$Q_0 = 3500\ m^3/j$
$C_{0,DBO5} = 130\ g\ BOD_5/m^3$
$C_{0,NH4} = 30\ g\ TKN/m^3$
$C_{e,NH4} = 2\ g\ N\text{-}NH_4/m^3$
$j_{BOD5} = 4\ g\ BOD_5/m^2{*}d$
$j_{NH4} = 0.9\ g\ N\text{-}\ NH_4/m^2{*}d$
$a_{S,rock} = 80\ m^2/m^3$
$a_{S,plastic.} = 140\ m^2/m^3$

Rock packing filter

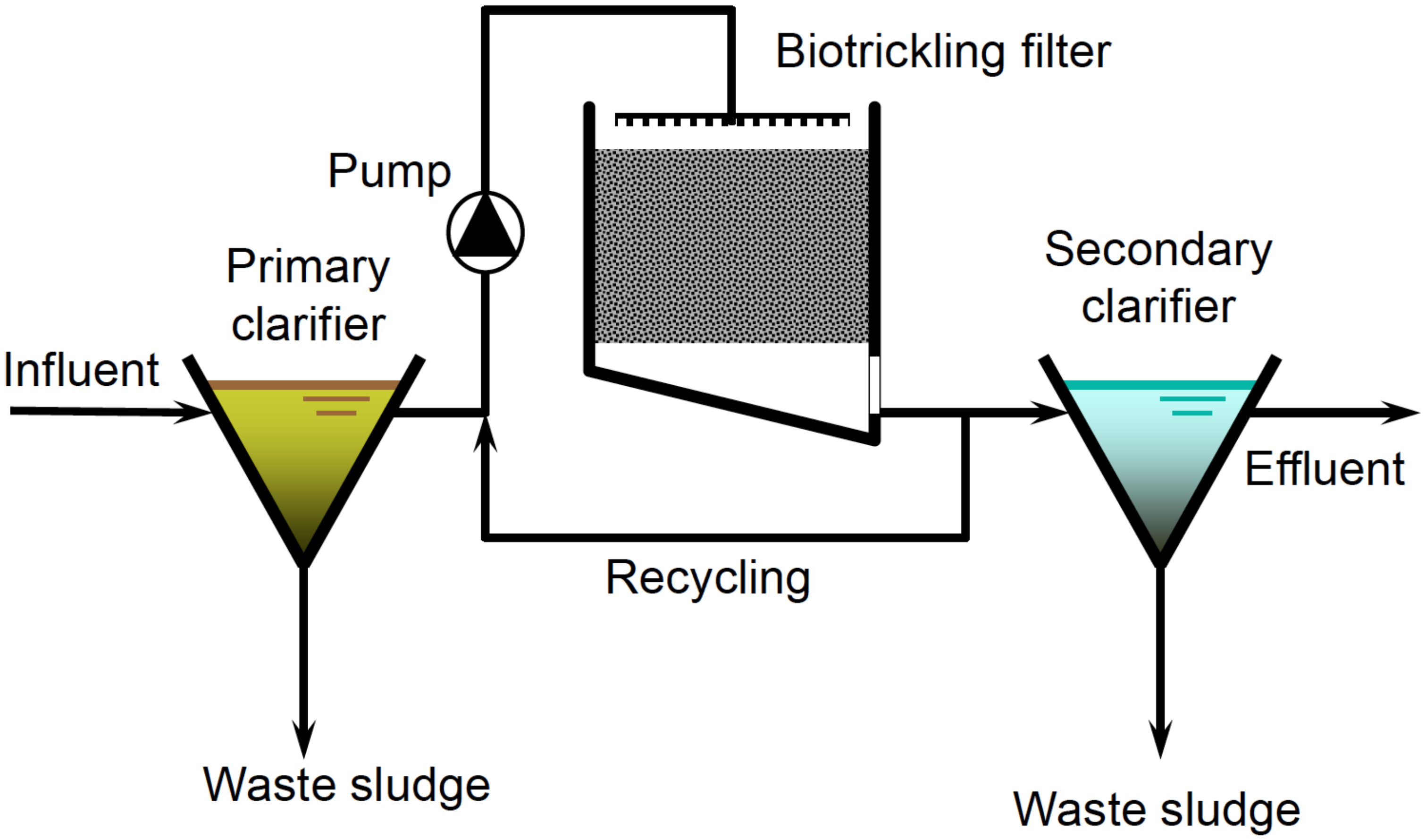
$V_{TF,BOD} = 1420\ m^3\ (1140\ m^3)$
$V_{TF,nit} = 2880\ m^3\ (2280\ m^3)$

Plastic packing filter

$V_{TF,BOD} = 815\ m^3\ (815\ m^3)$
$V_{TF,nit} = 1645\ m^3\ (1630\ m^3)$

We take the relatively conservative number. You can also try the calculation with 7 g /m2*d

Need to maintain certain hydraulic load by recycling to avoid dry up of packing material



Hydraulic load of the trickling filter

type of packing material	hydraulic load c_h (m / h)	
	without nitrification	with nitrification
rocks	0.5 – 1.0 **(0.42)**	0.4 – 0.8 **(0.20)**
plastic	1.0 – 2.0 **(1.07)**	0.8 – 1.6 **(0.53)**

Plastic material is easier to dry out.

$$c_h = \frac{Q_0 / 24}{V_{TF} / H}$$

$H_{TF,rocks} = 4$ m
$H_{TF,plastic.} = 6$ m
$Q_0 = 3500$ m^3/d

Biotrickling filter is not designed for denitrification as the units usually get contact with O_2 well.

- But it is possible to achieve by separating an anoxic trickling filter.

Dimensioning a denitrifying trickling filter

Determination of nitrogen to denitrify

HOMEWORK 4

$$C_{den} = C_{0,TKN} + C_{0,NO_3} - 0.045 \cdot C_{0,BOD_5} - C_{e,TKN} - C_{e,NO_3}$$

$$C_{den} = 30 + 0 - 0.045 \times 130 - 10 = 14.15$$

Determination of needed denitrification capacity

$$r_{den} = \frac{C_{den}}{C_{0,BOD_5}}$$

$$r_{den} = \frac{14.15}{130} = 0.11$$

Calculation of surface load

$$B_{A,BOD_5} = e^{(0.182 - r_{den})/0.04}$$

An empirical formula to use.

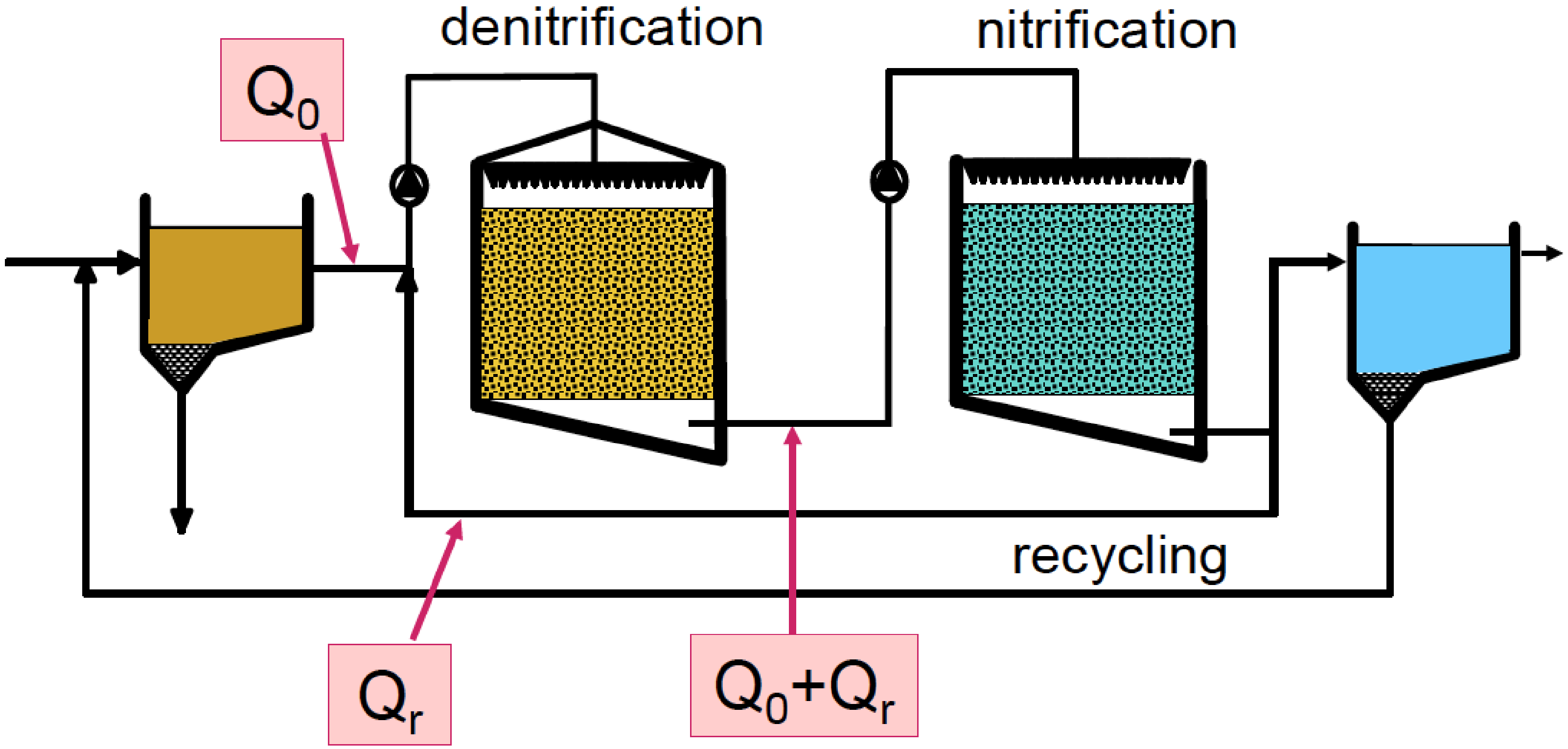
$$B_{A,BOD_5} = e^{(0.182-0.11)/0.04} = 5.90$$

Calculation of total surface needed for denitrification

$$A_{den} = \frac{Q_0 \cdot C_{0,BOD_5}}{B_{A,BOD_5}}$$

$$A_{den} = \frac{Q_0 \cdot C_{0,BOD_5}}{B_{A,BOD_5}} = \frac{3500 \cdot 130}{5.90} = 77'000 m^2$$

- Effluent of denitrification goes to nitrification with some BOD left, which needs to be degraded on the top of the nitrification reactor.
- We also try to design the effluent of denitrification to still contain some nitrate, for example, 1 g $NO_3/m^{3.}$ (because this is an **pre-denitrification** process)



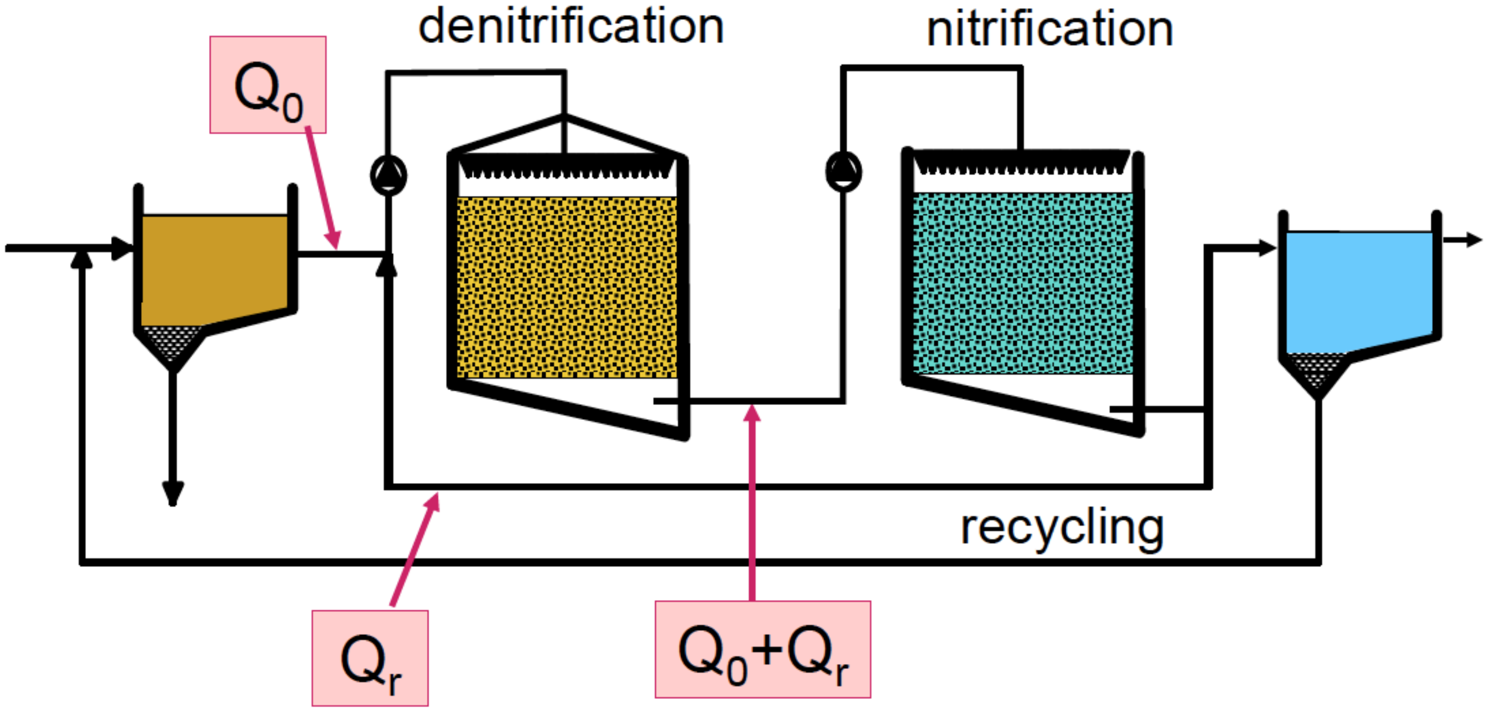
Recirculation coefficient of a denitrifying trickling filter: how much nitrate needs to be brought back, while make sure some nitrate is still left:

$$Q_0 C_{0,NO_3} + Q_r C_{e,NO_3} \geq Q_0 C_{den} + \left(Q_0 + Q_r\right) \times C_{e,den}$$

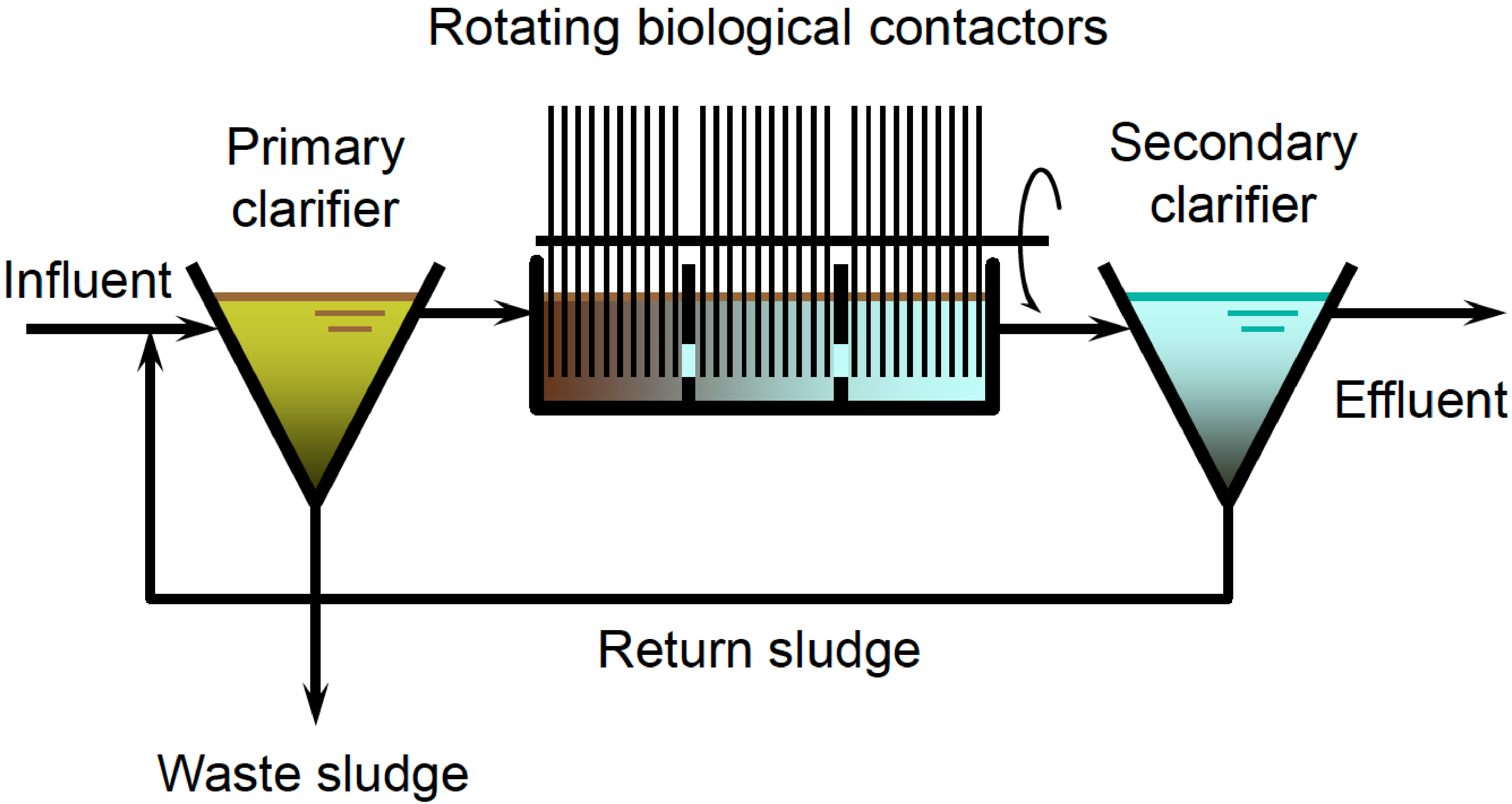
$$Q_0 C_{0,NO_3} + Q_r C_{e,NO_3} > Q_0 C_{den} + \left(Q_0 + Q_r\right) \times 1 \quad \text{g } NO_3/m^3$$

$$r = Q_r / Q_0 > \left(C_{den} - C_{0,NO_3} + 1\right) / \left(C_{e,NO_3} - 1\right) \cong \left(C_{den} + 1\right) / \left(C_{e,NO_3} - 1\right)$$

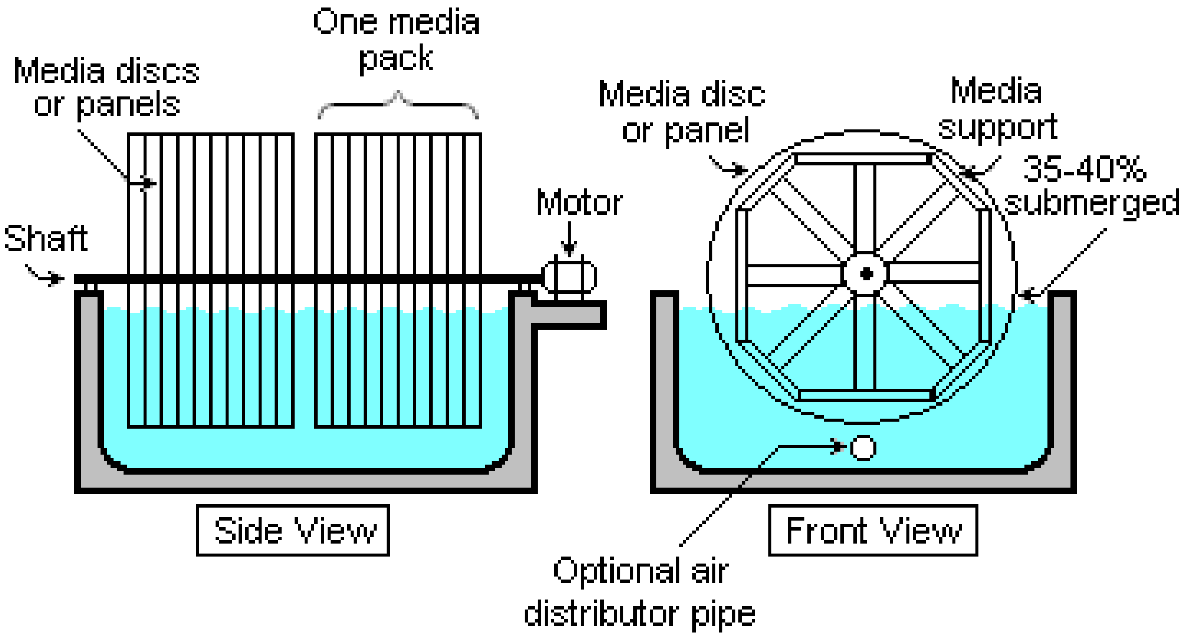
$$\boxed{\text{our example: } r = Q_r/Q_0 > (14.15 + 1) / (10 - 1) = 1.68}$$



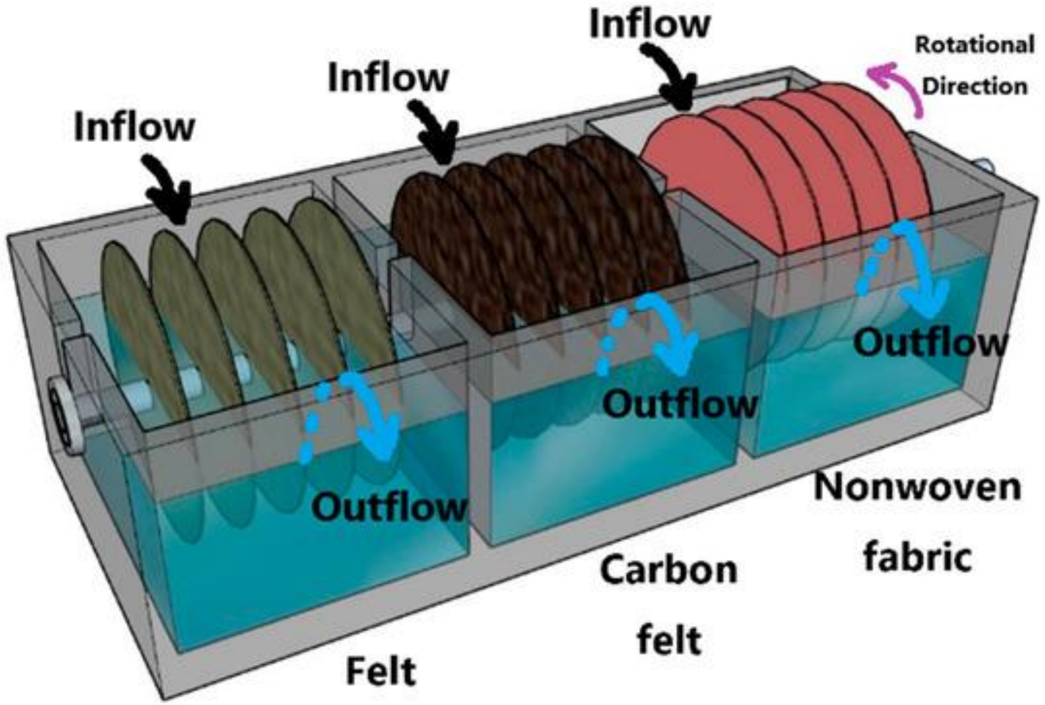
The rotating biological contactor process

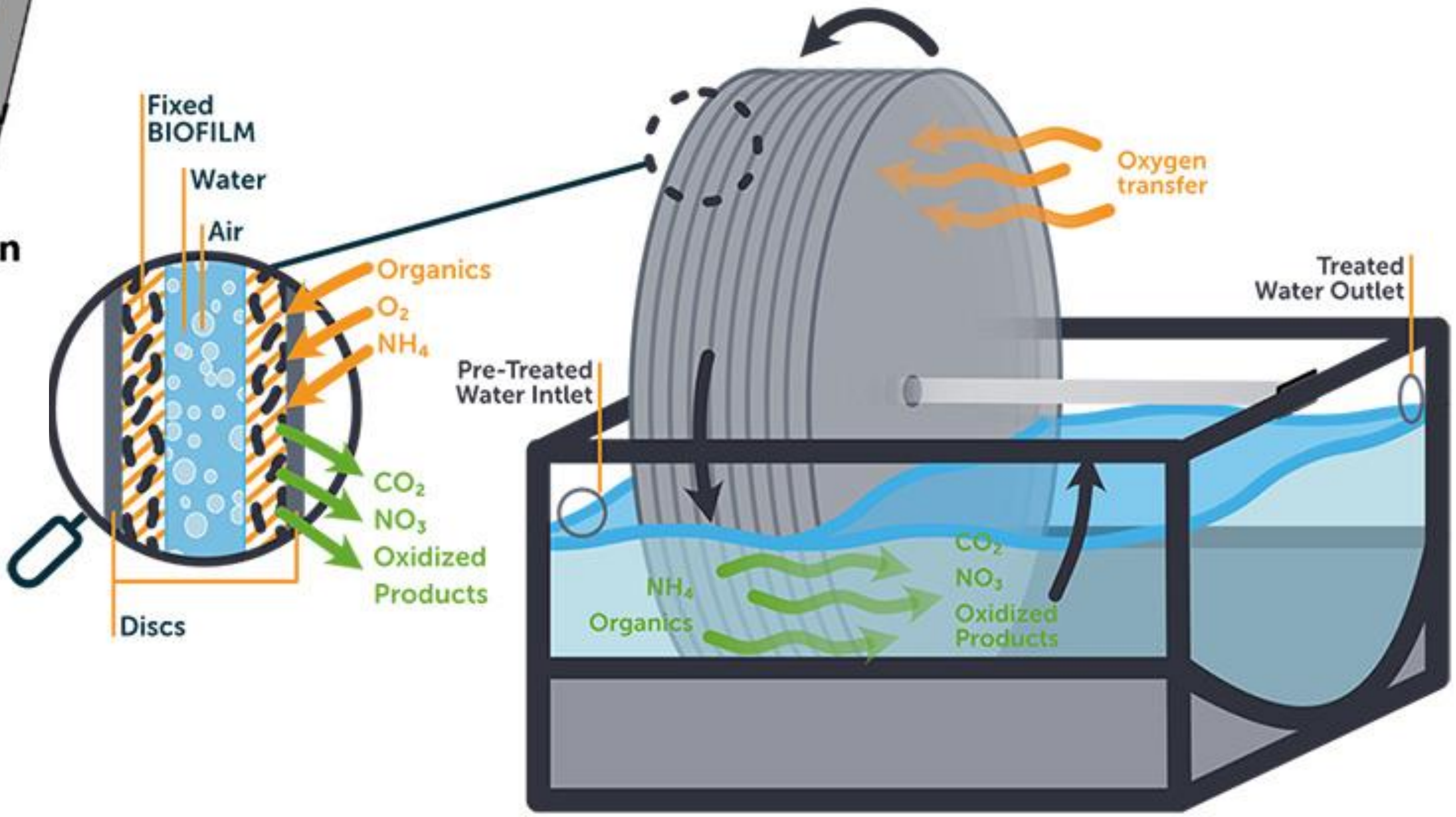


Rotating biological contactor:

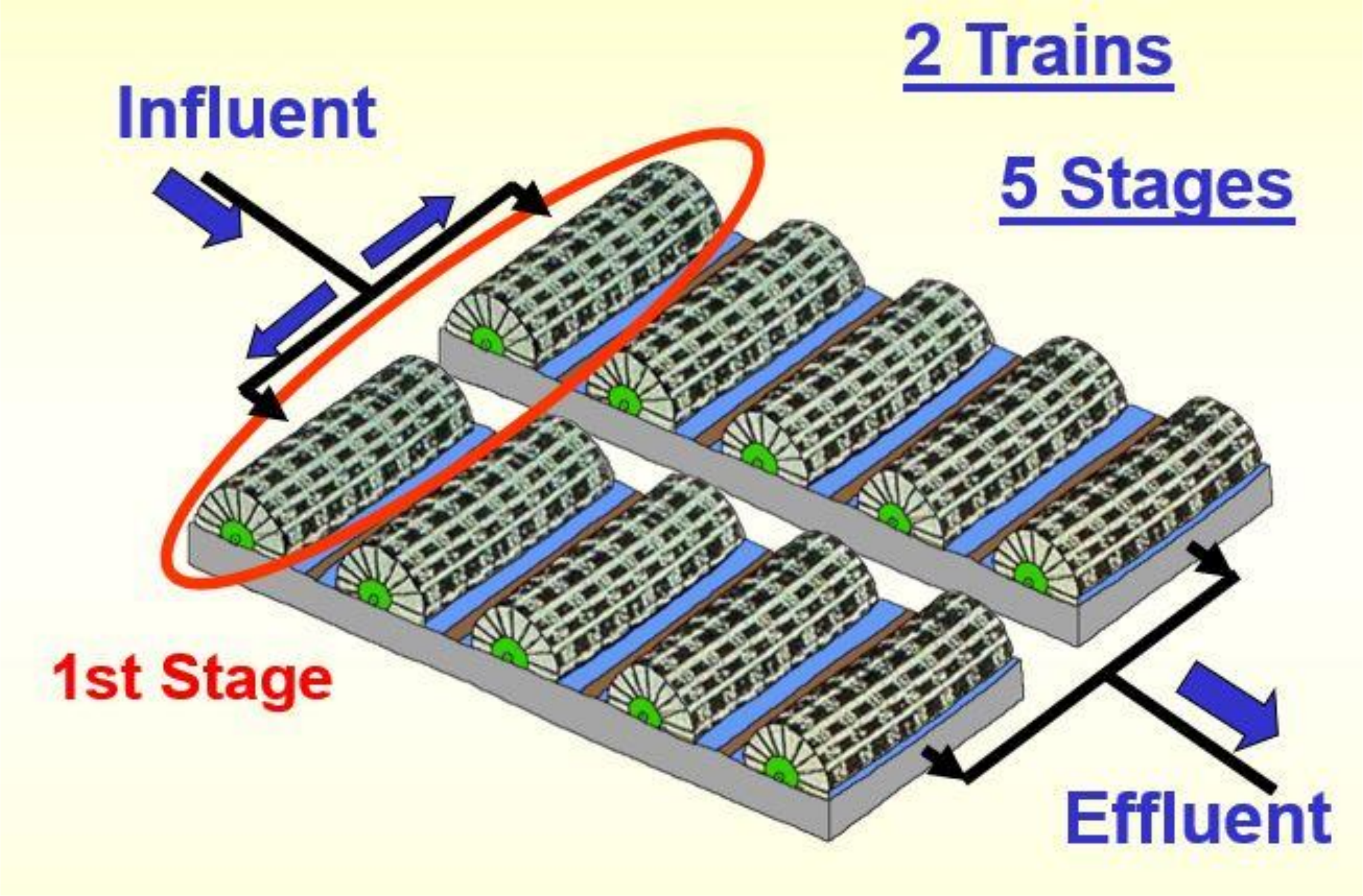


Rotating biological contactor:





Rotating biological contactor:



Biological contactors

HOMEWORK 4

$$B_A = \frac{Q_0 \cdot C_{0,BOD}}{A_{BC}}$$

B_A = surface load in g BOD_5 m^{-2} d^{-1}
Q_0 = flow rate of influent in m^3 d^{-1}
$C_{0,BOD}$ = concentration of influent BOD_5 in g m^{-3}
A_{BC} = total available colonisation surface in m^2

Typical values:

B_A = 8 - 12 g BOD_5 m^{-2} d^{-1} for elimination of BOD_5
= 4 - 5 g BOD_5 m^{-2} d^{-1} with nitrification included

Dimensioning of biological contactors:

Q_0 = 3500 m^3/d
$C_{0,BDO}$ = 130 g BOD_5/m^3

$$A_{BC} = \frac{Q_0 \cdot C_{0,BOD}}{B_A} = \frac{3500 \cdot 130}{8(4)} =$$

nitrification	
without	with
$57'000 m^2$	$114'000 m^2$
Modules of $10'000 m^2$	
6	12

Dimensioning a nitrifying biological contactors with specific surface loads

$$A_{tot} = A_{BOD_5} + A_{nit} = \frac{Q_0 \cdot C_{0,BOD_5}}{j_{BOD_5}} + \frac{Q_0 \cdot \left(C_{0,NH_4} - C_{e,NH_4}\right)}{j_{NH_4}}$$

$$\left.\begin{aligned}
Q_0 &= 3500\ \mathrm{m^3/d} \\
C_{0,BOD5} &= 130\ \mathrm{g\ BOD_5/m^3} \\
C_{0,NH4} &= 30\ \mathrm{g\ TKN/m^3} \\
C_{e,NH4} &= 2\ \mathrm{g\ N\text{-}NH_4/m^3} \\
j_{BOD5} &= 12\ \mathrm{g\ BOD_5/m^2{*}d} \\
j_{NH4} &= 1.5\ \mathrm{g\ N\text{-}NH_4/m^2{*}d}
\end{aligned}\right\}
\quad
\begin{aligned}
A_{DB} &= 38'000\ \mathrm{m^2} + 66'000\ \mathrm{m^2} \\
&= 104'000\ \mathrm{m^2} \\
&\quad (114'000\ \mathrm{m^2})
\end{aligned}$$

Dimensioning a denitrifying biological contactor

Determination of nitrogen to denitrify

$$C_{den} = C_{0,TKN} + C_{0,NO_3} - 0.045 \cdot C_{0,BOD_5} - C_{e,TKN} - C_{e,NO_3}$$

Determination of needed denitrification capacity

$$r_{den} = \frac{C_{den}}{C_{0,BOD_5}}$$

Calculation of surface load

$$B_{A,BOD_5} = e^{(0.20 - r_{den})/0.04}$$

An empirical formula to use.
Slightly different from before.

Calculation of total surface needed for denitrification

$$A_{den} = \frac{Q_0 \cdot C_{0,BOD_5}}{B_{A,BOD_5}}$$

The previous configurations are rarely used in new plants especially for larger facilities

Because they have limited O_2 control, a relatively large footprint, and are difficult to reach very low TN in effluent.

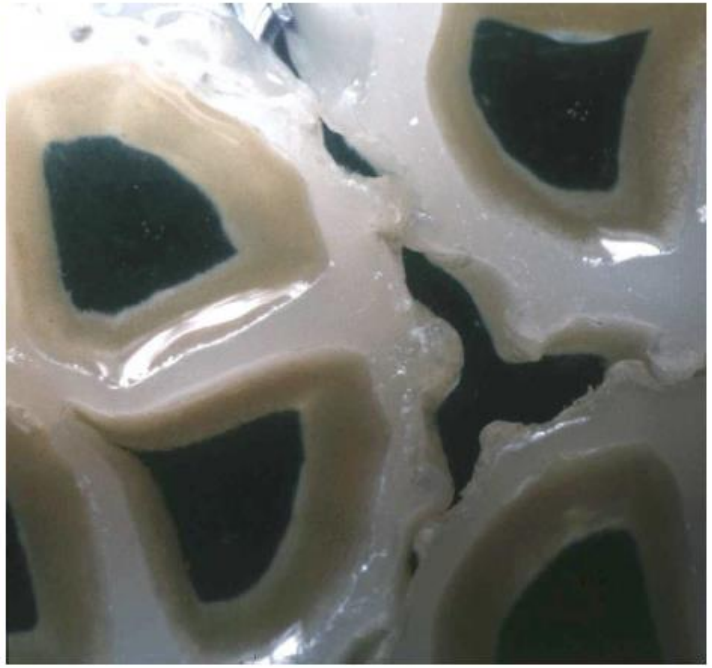
- New plants typically use **suspended growth or hybrid systems**:
- **Activated sludge with anoxic–aerobic zones** (e.g., pre/post-denitrification)
- **SBR** (in small, de-centralized systems)
- **Integrated fixed-film activated sludge (IFAS)** or **MBBR** (Moving Bed Biofilm Reactor)

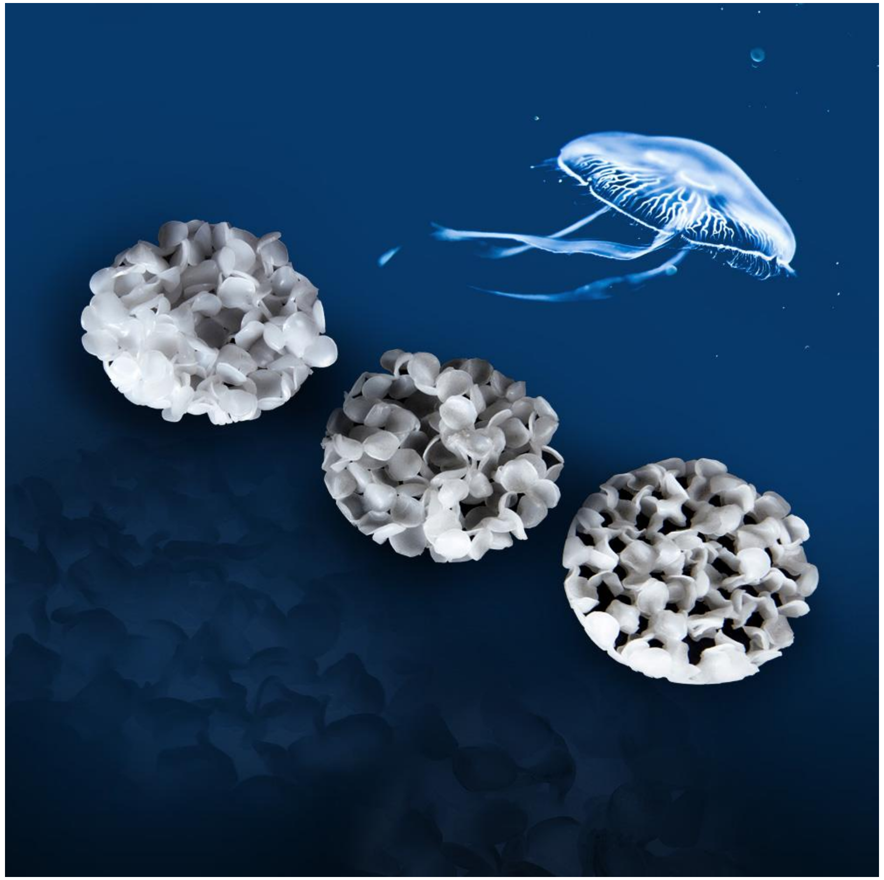
Design of MBBRs (Moving bed biological reactors)

- **You can use this method to upgrade existing activated sludge WWTPs**
- **Carrier density is slight lighter than water, but sink if covered by biofilms**

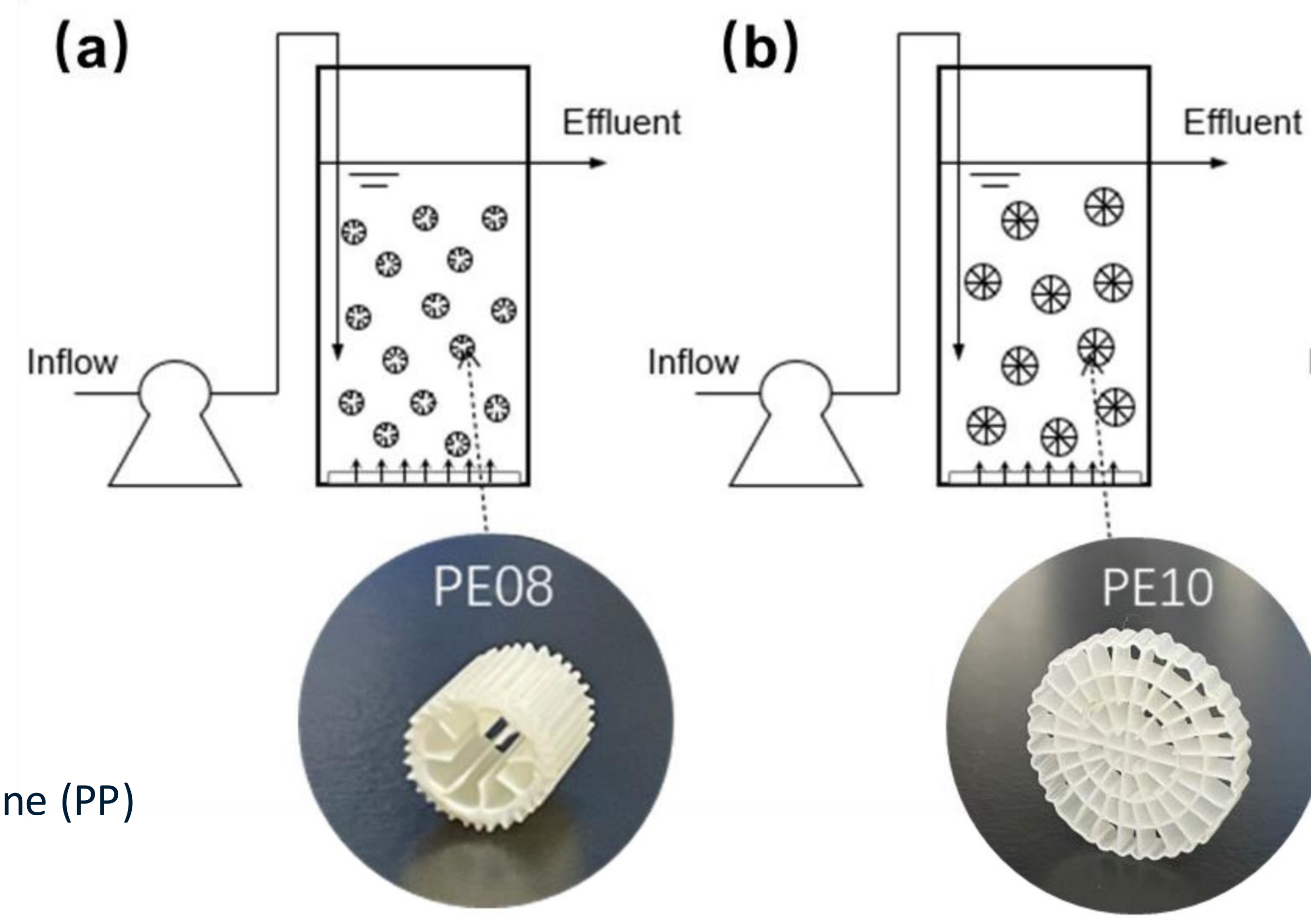
Carrier Material

Biofilm example





GeoTierre

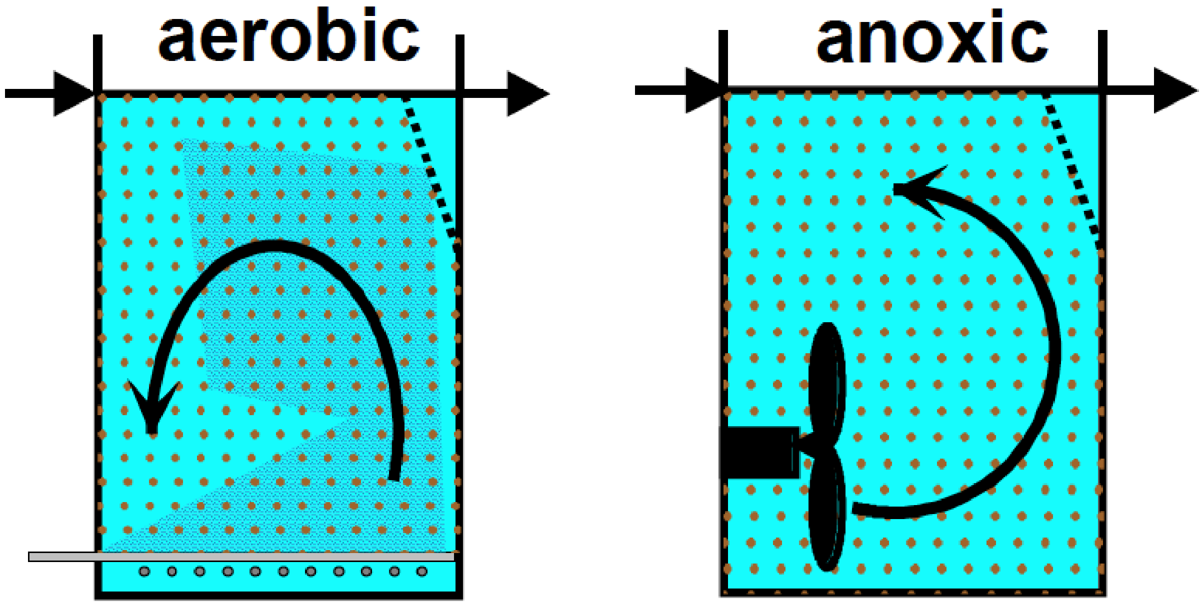


Common materials are:
high-density polyethylene (HDPE) and polypropylene (PP)

https://www.mdpi.com/2073-4441/15/13/2415

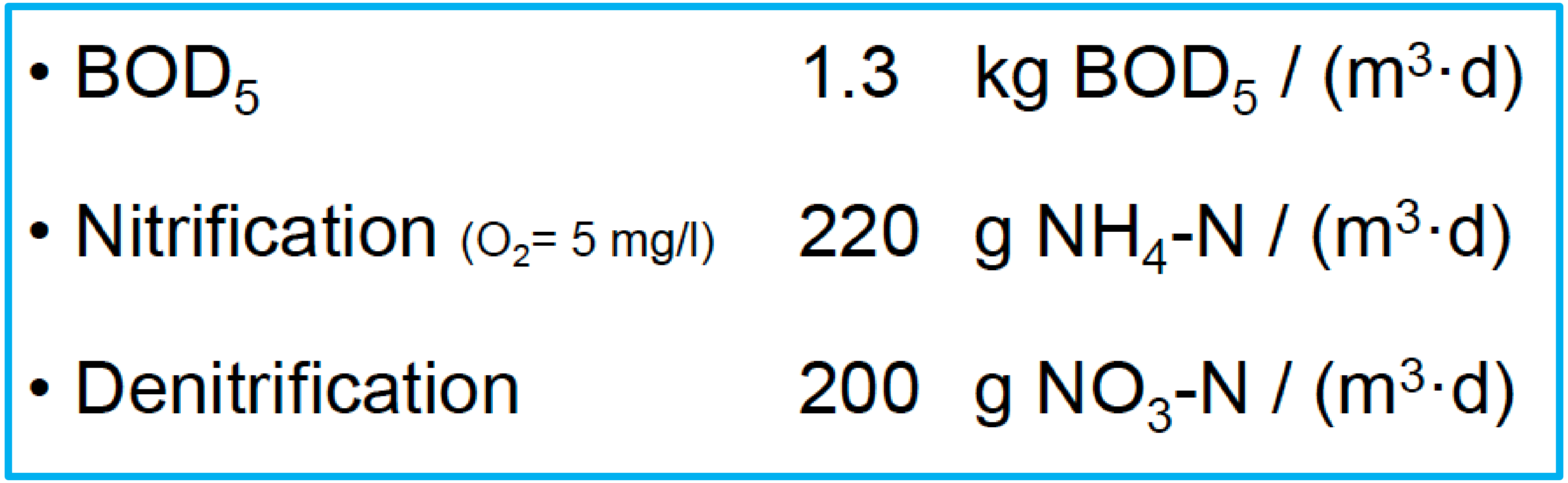
Moving Bed Biological Reactors (MBBRs)

- Carrier is moving and circulating
- control of biofilm thickness
- no special backwash installation
- active aeration used for mixing process



Elimination Rates

- Temperature 10°C, filling degree 65%
- Specific reactor volume elimination rates



• BOD_5	1.3	kg BOD_5 / ($m^3 \cdot d$)
• Nitrification (O_2= 5 mg/l)	220	g NH_4-N / ($m^3 \cdot d$)
• Denitrification	200	g NO_3-N / ($m^3 \cdot d$)

Moving Bed System

Advantages

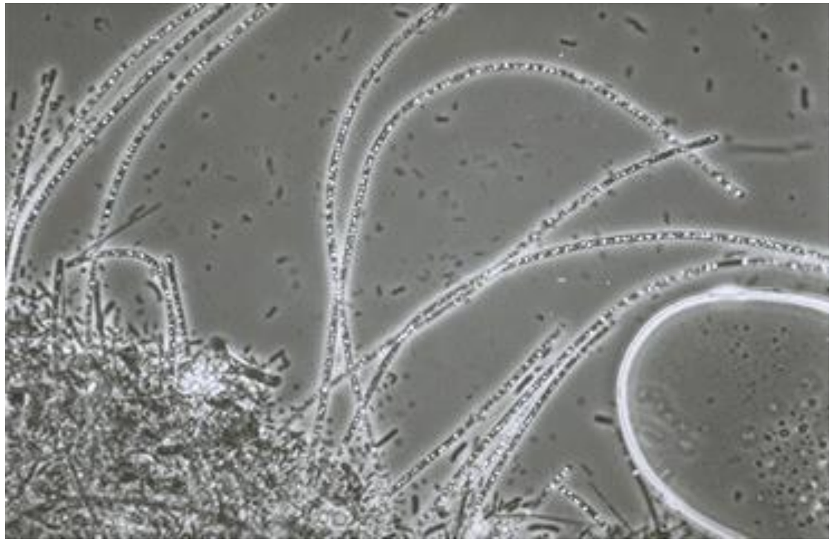
- use of existing buildings
- reduce bulking sludge
- simple operation
- smaller hydraulic load on the secondary clarifier
- load variation

Disadvantages

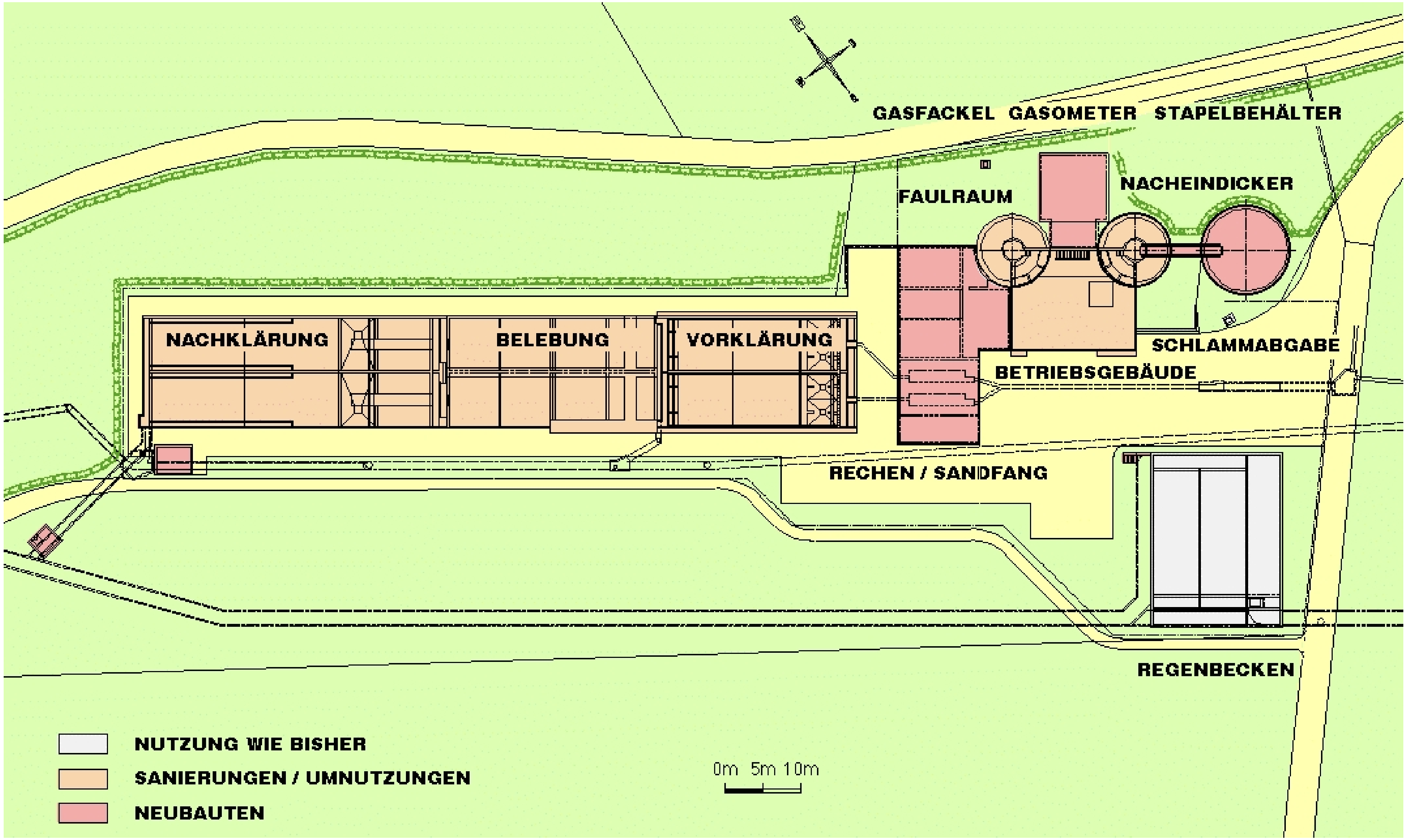
- higher energy consumption (less than activated sludge)
- optimisation of energy, control technique

Bulking sludge

- a problem of poor settling and compaction of activated sludge, caused by the excessive growth of filamentous bacteria.
- This leads to a cloudy effluent because the sludge particles do not settle properly in the clarifier, and in severe cases, the sludge can overflow.
- Causes include a low food-to-microorganism (F/M) ratio, low dissolved oxygen (DO), nutrient deficiency, and other factors that promote filamentous growth.



Example: ARA Rehmatte, Fislisbach



Characteristics

Wastewater

Dry weather	DW	max.	263	m^3/h
		averg.	179	m^3/h
Rain weather		min.	108	m^3/h
	RW	max.	526	m^3/h
	BOD_5		640	kg/d
	COD		1200	kg/d
	N_{tot}		123	kg/d
	P_{tot}		25	kg/d

Wastewater Treatment

- Primary Clarifier
  2 x 357 m^3
- Biology
  2 x 538 m^3
- Secondary Clarifier
  2 x 203 m^2

Parameters

Moving Bed Biofilm System

- Temperature 10°C
- Filling 65%
- effective surface
  500m^2/m^3
- O$_2$-conc. in Reactor
  3.5 mg/l
- full nitrification
- Yield
  Y'= 0.51 gCOD/gCOD

Activated Sludge System

- Temperature 10°C
- Biomass (BM) conc. in reactor
  TSS_R= 2.5 gTSS/L
- full nitrification
  (sludge retention time 10 d)
- Yield
  Y'= 0.56 gCOD/gCOD

Old system: Activated Sludge

Sludge age $$\theta_{aerob} = \frac{Volume_{reactor} \times TSS_{reaktor}}{X_{excess}}$$

excess = waste

$$Volume_{reactor} = \frac{X_{excess} \times \theta_{aerob}}{TSS_{reactor}}$$

$$X_{excess} = Y' \times COD = 0.56 \times 1200 \text{ kgCOD/d}$$

$$= 672 \text{ kgCOD/d} = 473 \text{ kgTSS/d}$$

$$Volume_{reactor} = \frac{473 \text{ kgTSS/d} \times 10 \text{ d}}{2.5 \text{ kgTSS/m}^3}$$

$$\underline{\underline{Volume_{reactor} = 1'890 \text{ m}^3}}$$

Current volume is not enough

Upgrade: MBBR

HOMEWORK 4

BOD_5 removal

Volume needed for BOD_5 degradation

Elimination rate

1.3 kg BOD_5 / m^3*d (10°C, 65%)

Volume

$$V_{BOD_5,reactor} = \frac{640\ kg\ BOD_5\ /\ d}{1.3\ kg\ BOD_5\ /\ m^3 * d}$$

$$V_{BOD_5,reactor} = 492\ m^3$$

Nitrification

Nitrogen mass balance:

- Nitrogen in influent

  = 123 kg N/d
- Nitrogen in excess sludge

  = 640 kg BOD_5/d x 0.045 kg N/kg BOD_5 = 29 kg N/d
- Nitrogen (NH_4-N) in effluent

  = 2 mg/l x 179 m^3/h x 24 h = 9 kg NH_4-N/d
- Nitrogen to nitrify

  = 123 – 29 - 9 = 85 kg N/d

Upgrade: MBBR

HOMEWORK 4

Nitrification

Volume needed for NH_4-N - Nitrification

- Elimination rate

  0.193 kg NH_4-N / m^3*d
- Volume

$$V_{NH_4\text{-N,reactor}} = \frac{85\ \text{kg}\ NH_4\ \text{-N / d}}{0.193\ \text{kg}\ NH_4\ \text{-N / m}^3 * \text{d}}$$

$$\underline{V_{NH_4\text{-N,reactor}} = 440\ \text{m}^3}$$

Total Volume

V = 492 m^3 + 440 m^3

$\underline{= 923\ m^3}$

available 1’076 m^3

(130 m^3 for precipitation/flocculation)

Upgrade: MBBR

Check secondary sedimentation for rain weather, this is to ensure good solids-liquid separation

- Given: Criteria hydraulic surface load < 1.5 m/h

$$\frac{526\ \text{m}^3/\text{d}}{2 \times 203\ \text{m}^2} = 1.3\ \text{m}/\text{h}$$

Comparison: Area / Volume

Area	m^2/PE	%
Activated Sludge	7.4	740
Biofilter	1.0	100
Moving Bed	3.6-4.3	360-430

Next week

Volume	L/PE	%
Activated Sludge	260	325
Biofilter	80	100
Moving Bed	125-150	160-190

Conclusion: Use of MBBR

Moving biological biofilm system could be considered as an alternative process to the conventional treatment processes (activated sludge) especially in case of

- **renewal / extension / increasing elimination rates**
- **use of existing buildings (reactors)**

Feature	**Activated Sludge (AS)**	**Moving Bed Biofilm Reactor (MBBR)**
Biomass Growth	Suspended flocs	Attached biofilm on plastic carriers
Required Area	Larger (requires large aeration tank AND secondary clarifiers)	Smaller (higher biomass concentration in tank)
Nutrient Removal	Excellent (flexible for BNR/BPR)	Limited (typically requires multiple stages or hybrid systems)
Effluent Solids	Typically very low TSS (excellent clarification)	Can sometimes have higher TSS from sloughed biofilm
Shock Load Resistance	Lower (biomass is sensitive to sudden changes)	Higher (stable biofilm on carriers resists washout)
Sludge Handling	Higher Sludge Production	Lower Sludge Production