

# ENV-405 Session 2

## Wastewater treatment

### Lecture 6 Dec 9

Professor Wenyu Gu

Slides acknowledgment: Christof Holiger, Shilva Shretha

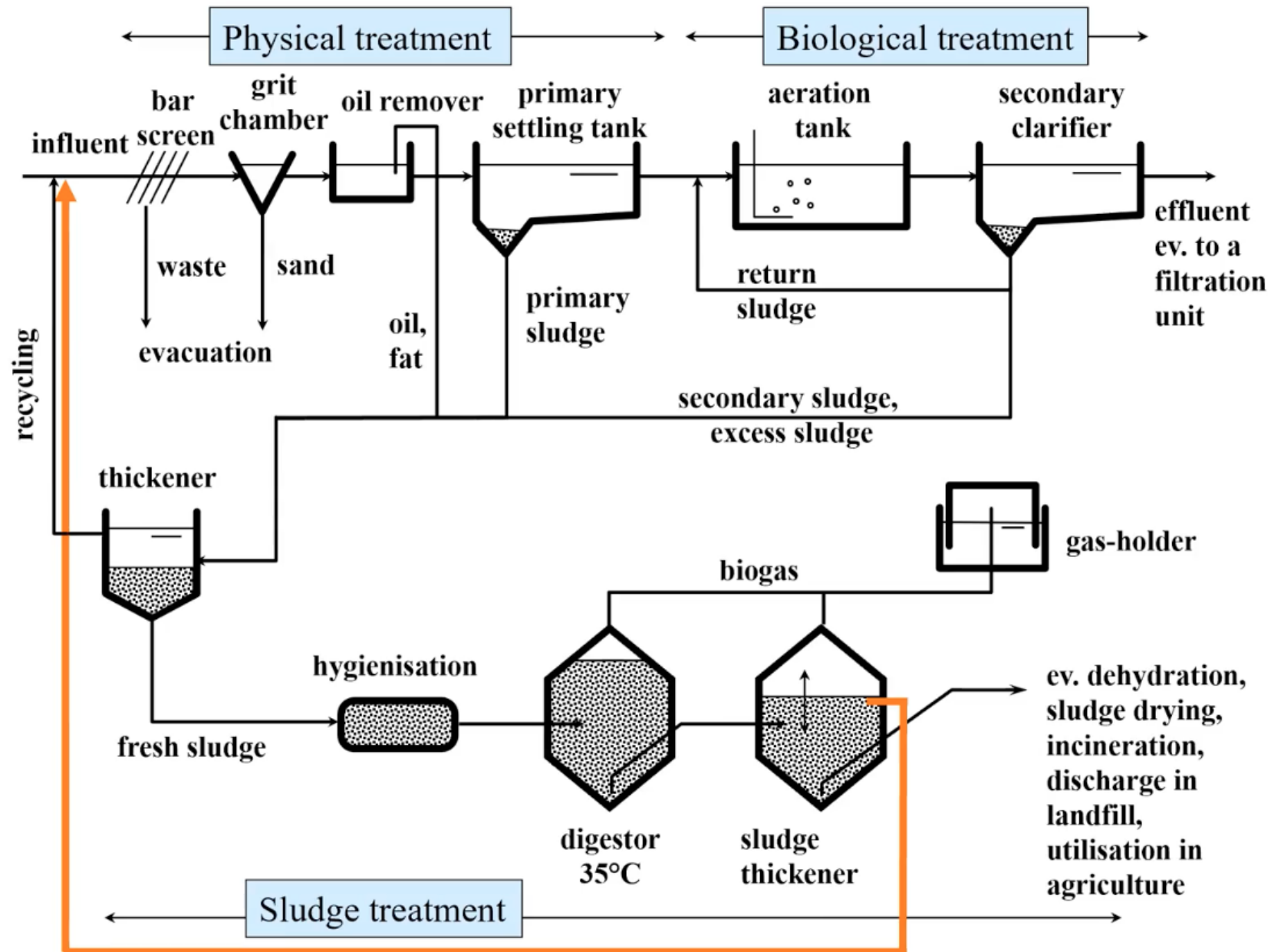
# Today's content:

- **Additional discussion about the Bern WWT example, SBR, overall nitrogen balance**
- **Nitrification-Anammox for sludge digestion effluent treatment**

Nitrification is the biological oxidation of ammonia  $\text{NH}_4^+$  to nitrite  $\text{NO}_2^-$ , while intentionally preventing the second step of oxidation from nitrite to nitrate  $\text{NO}_3^-$ .

- **Introduction to ASM mathematical model**

# Continue with Bern example:

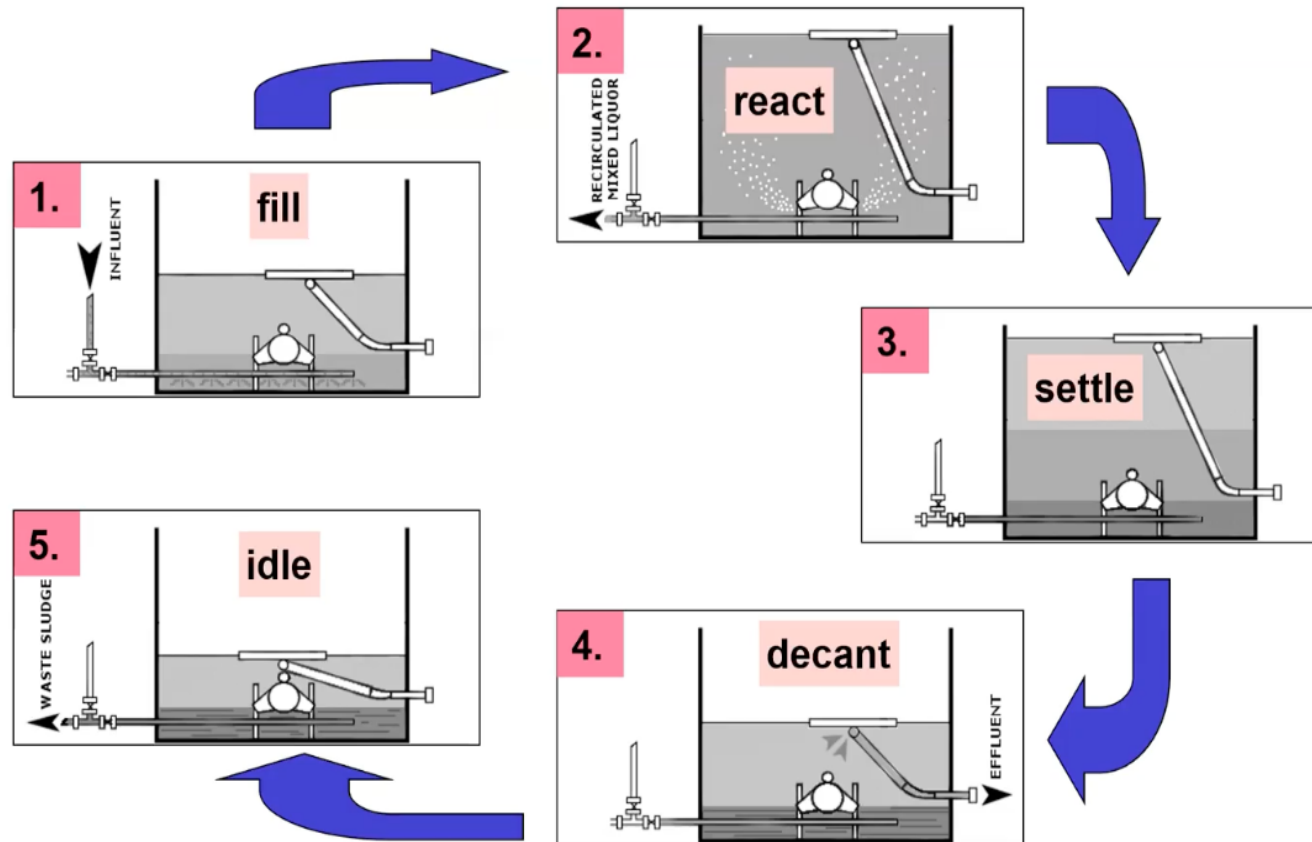


Co-substrate can help with digestion efficiency.

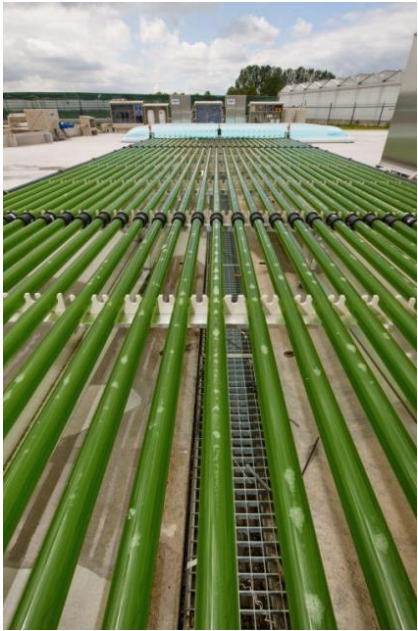
Some times small WWT transport sludge from thinkener to bigger WWT for digestion.

# Sequencing batch reactor

- In Bern, initially, SBR was used to treat the digestion effluent. The reactor was constructed for fat at the beginning.



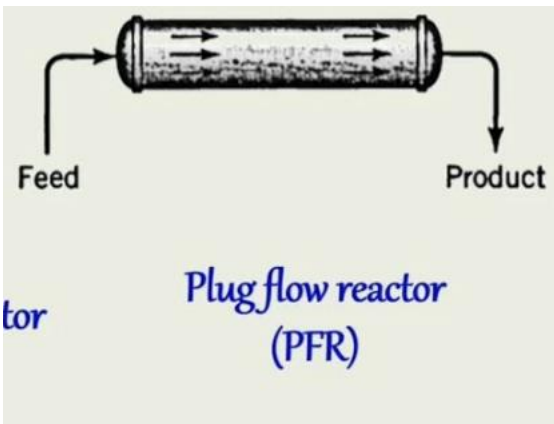
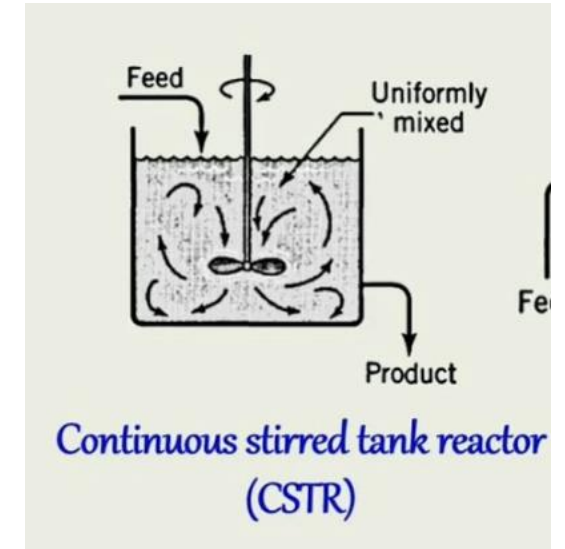
# Plug flow rxtr



# Sequencing batch reactor



# Continuous reactor

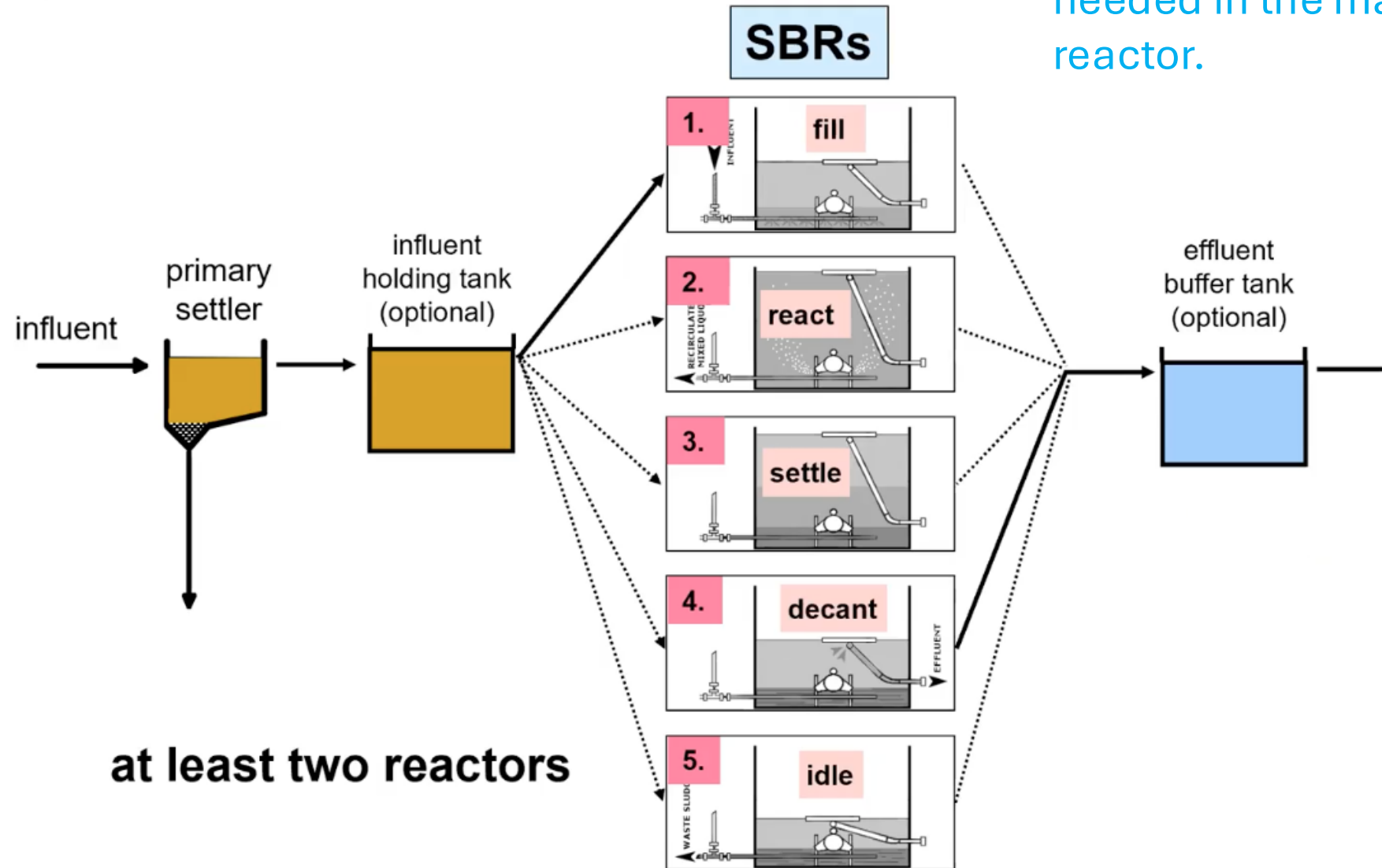


Just a reactor,  
no in and out.

Continuous in  
and out.

# Sequencing batch reactor

We have a homework calculating how much the SBR saves the treatment volume otherwise needed in the main biological reactor.



at least two reactors

# SBR can be used in mainstream WWT.

## ARA Birs WWTP based on SBR technology



### Key figures

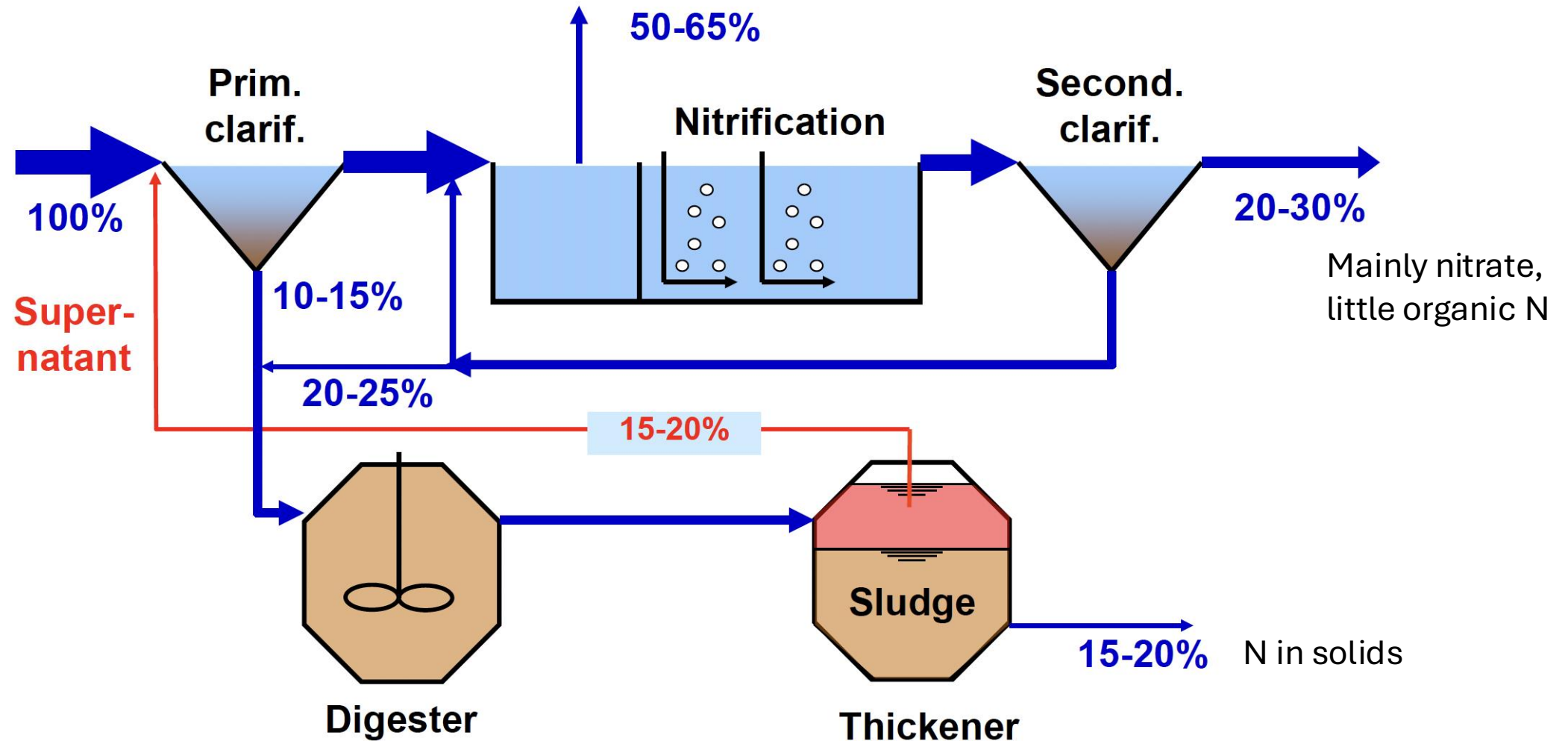
Capita connected: 83,000  
max. capacity: 150,000  
average load (COD): 100,000  
WW yearly volume: 9,550,000 m<sup>3</sup>/y  
Waste sludge: 1,930 t<sub>DW</sub>/y

Biogas production: 1,090,000 m<sup>3</sup>/y  
Electricity consumed: 3,280,000 kWh/y  
Electricity produced: 2,740,000 kWh/y (84%)

# Sludge Digestion Effluents

- high ammonium content (no nitrification occurs)
- low C/N ratio (carbon goes to  $\text{CO}_2$  and  $\text{CH}_4$ )
- high bicarbonate content (equilibrium with  $\text{CO}_2$  in gas phase)
- relatively high temperature ( $\sim 37^\circ\text{C}$ , vs  $15^\circ\text{C}$  of WW, microbial process is much faster at  $37^\circ\text{C}$ )
  
- Recycles 15-20% of influent-N into WWT as  $\text{NH}_4\text{-N}$

# N-flux in a WWTP with 70-80% N removal



# **Advance Nitrogen Treatments**

# Nitrification-Denitrification

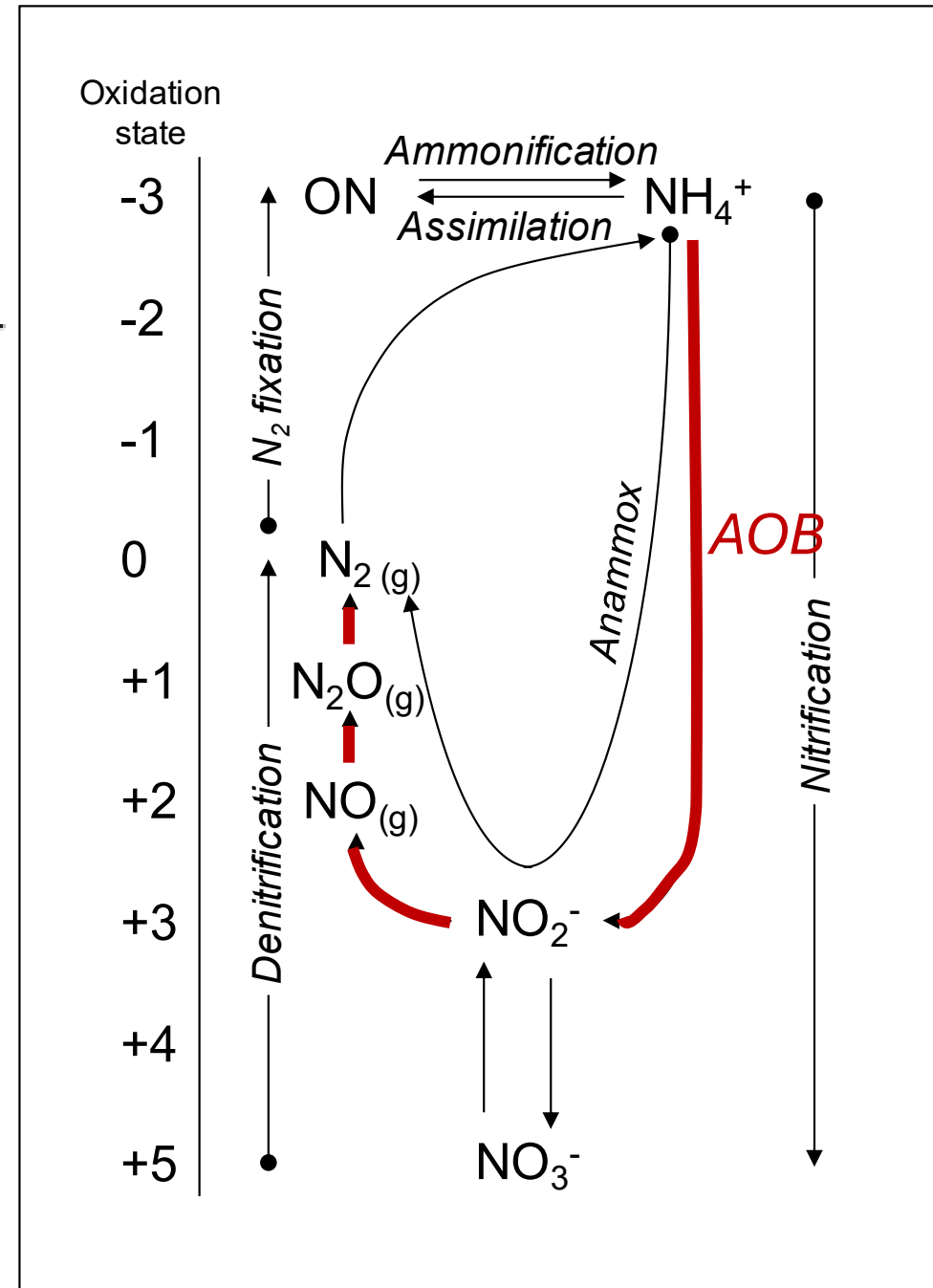
## “nitrite-shunt” process

Ammonia oxidation:  $\text{NH}_4^+ + 1.5 \text{O}_2 \rightarrow \text{NO}_2^- + \text{H}_2\text{O} + 2 \text{H}^+$

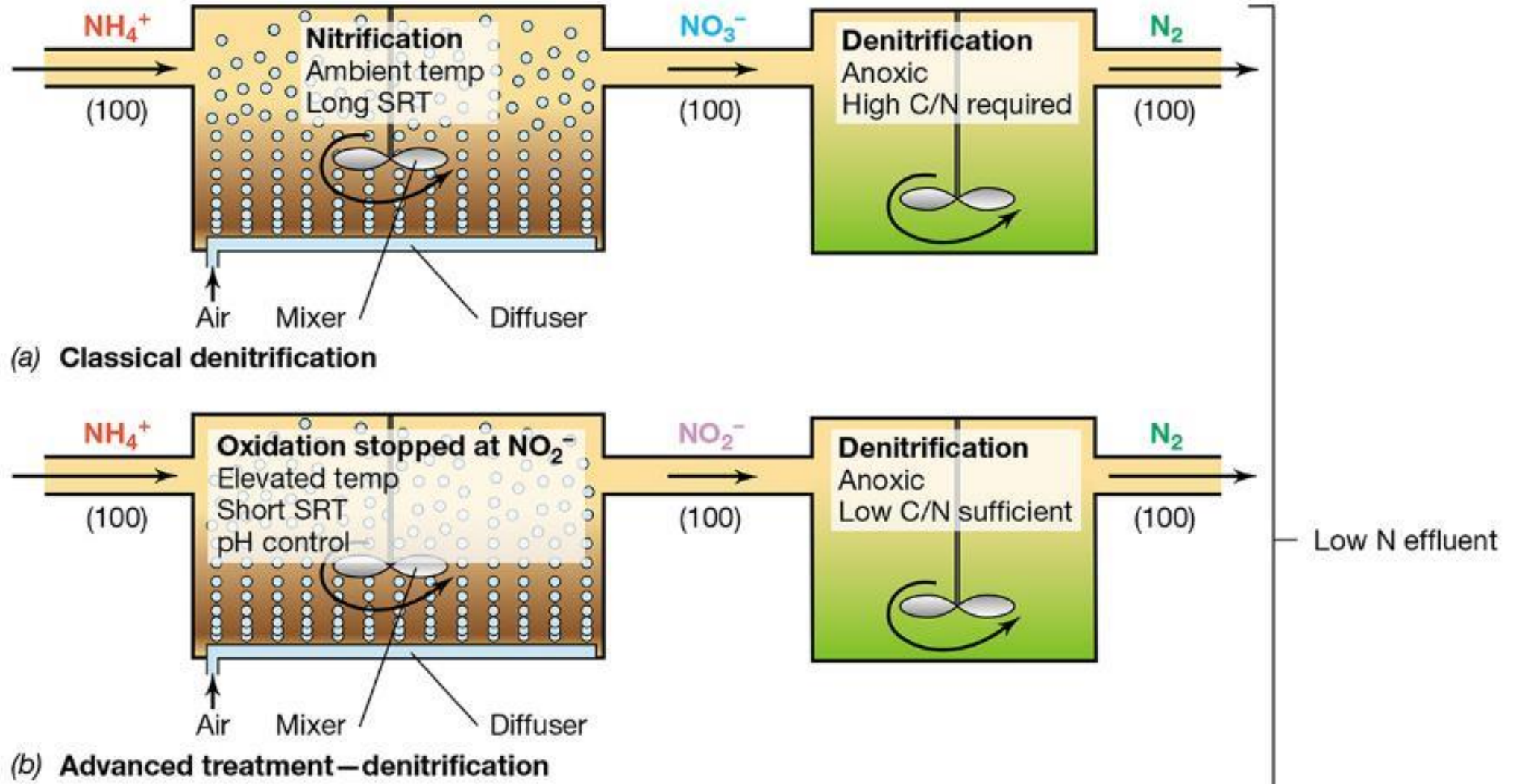
Denitrification:  $\text{NO}_2^- + 24 \text{ g COD} + \text{H}^+ \rightarrow 0.5 \text{N}_2$

(producing 9 g sludge biomass)

- Suppress activity of NOBs
- Carbon requirement reduced by ~40%
- Oxygen by ~25%
- Biomass by ~40%



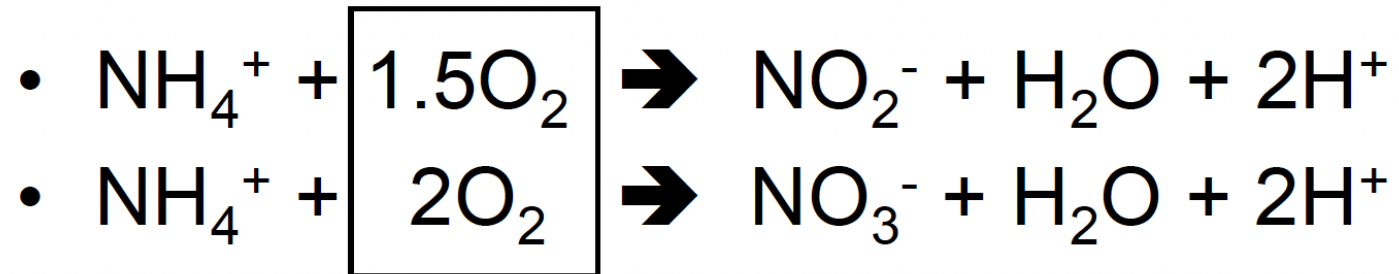
# Nitrification-Denitrification



# SHARON

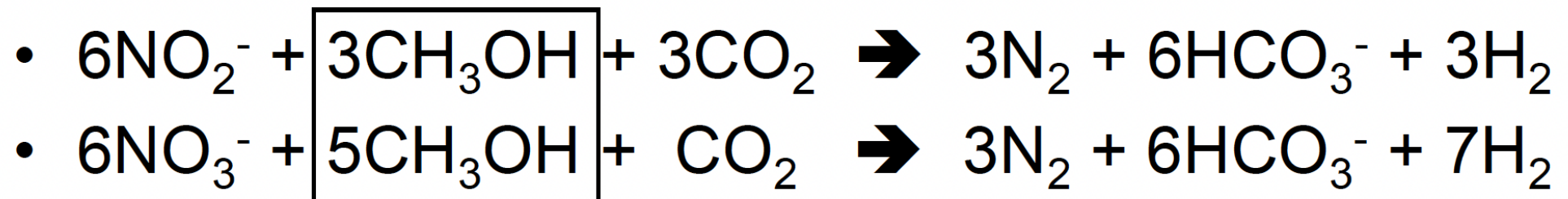
## Single reactor system for High activity Ammonium Removal Over Nitrite

### Nitrification



savings of 25%

### Dénitrification



savings of 40%

# SHARON operation

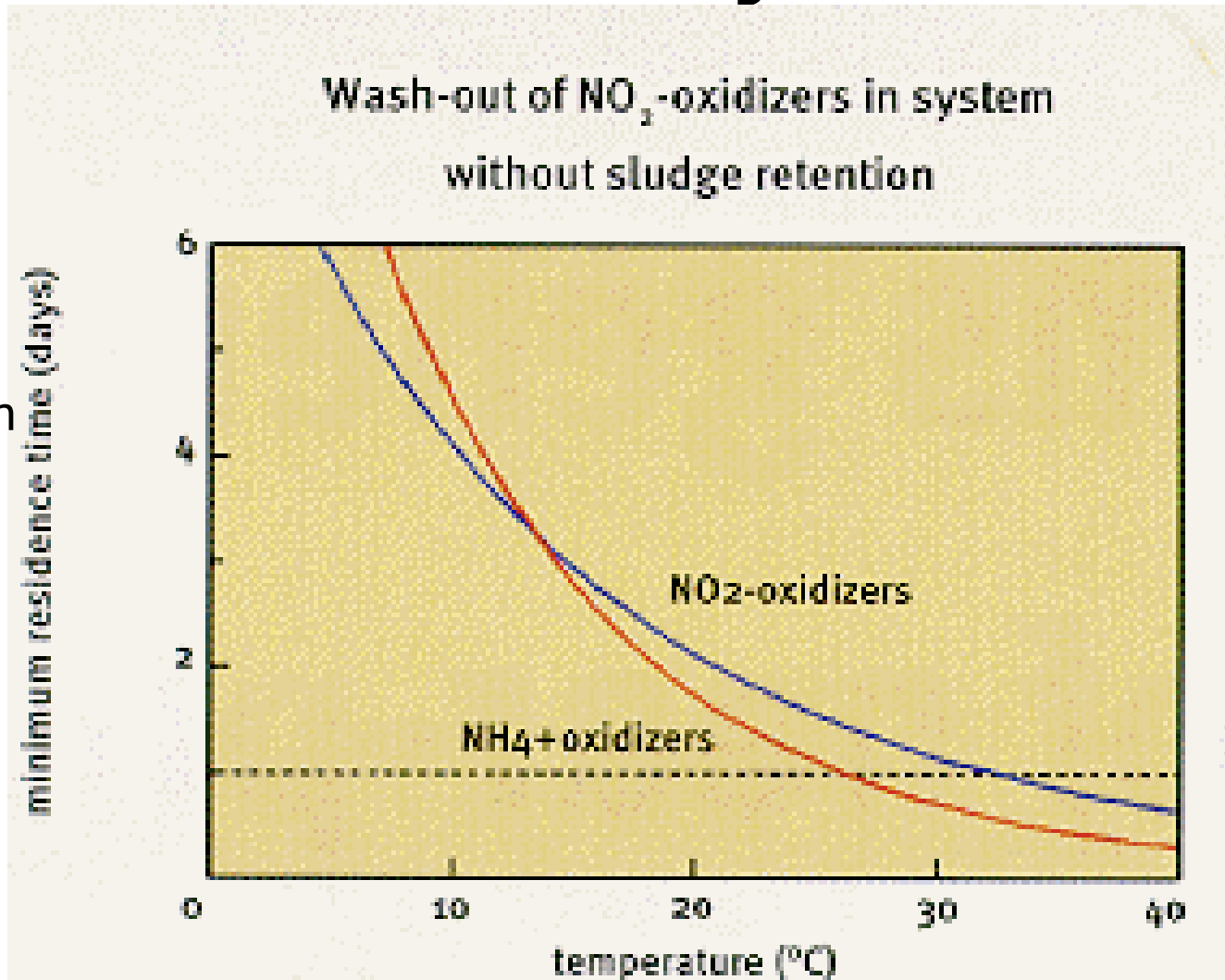
- **SHARON** = A system optimized for **forcing an imbalance** (AOB > NOB).
- It's a 1 reactor process, but not SRB; it's operated as a CSTR with continuous flow and short SRT, but O<sub>2</sub>/anoxic conditions alternate in frequencies of less than an hour.
- Quick intermittent O<sub>2</sub>/anoxic conditions, maintain a selective suppression of NOB. In one shared competitive environment, use intermittent oxygen is a tool to destabilize NOB.

# Technical problems to solve

1. Hinder nitrite oxidizing bacteria activity (NOB)
2. Avoid acidification of the system

# Selection of nitrifying bacteria: CSTR with HRT = 1 day

Minimal residence time in “CSTR”

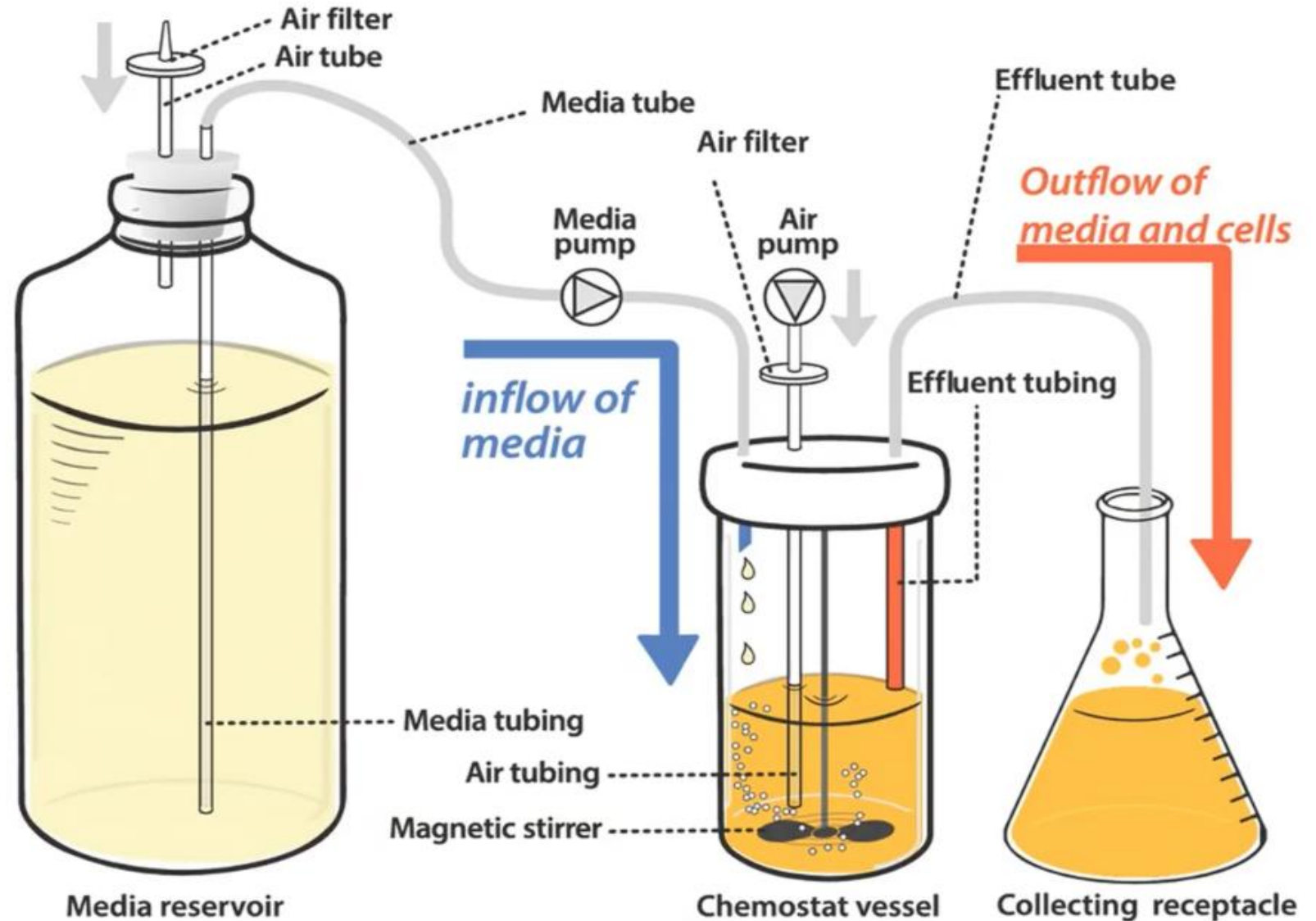


The influence of temperature (equations) on growth rate for *Nitrosomonas* and *Nitrobacter* are different (Lecture 2)

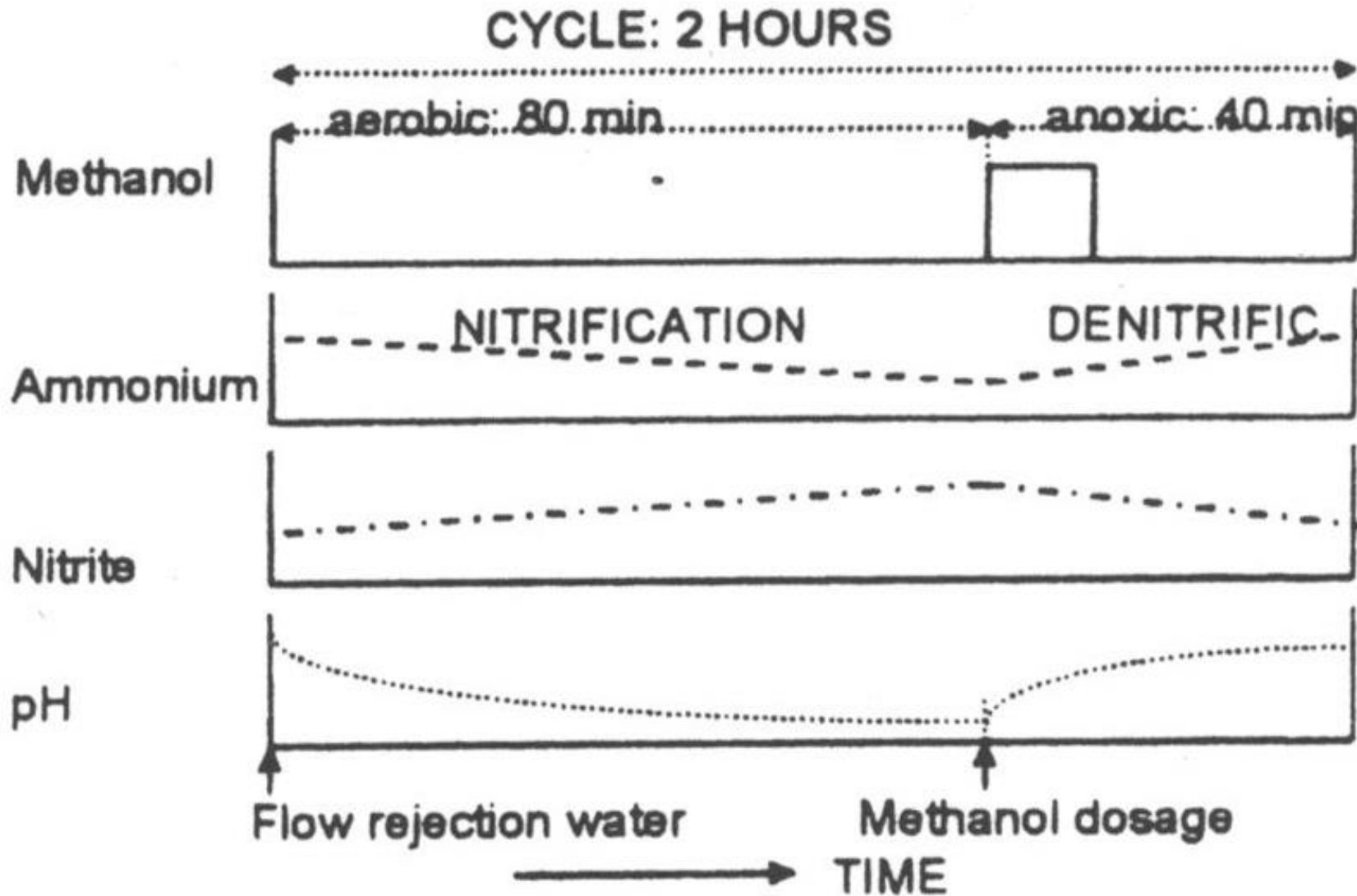
For example, at higher temperature at 30 C, if you choose 1 day HRT, nitrite oxidizers will be washed out.

# CSTR

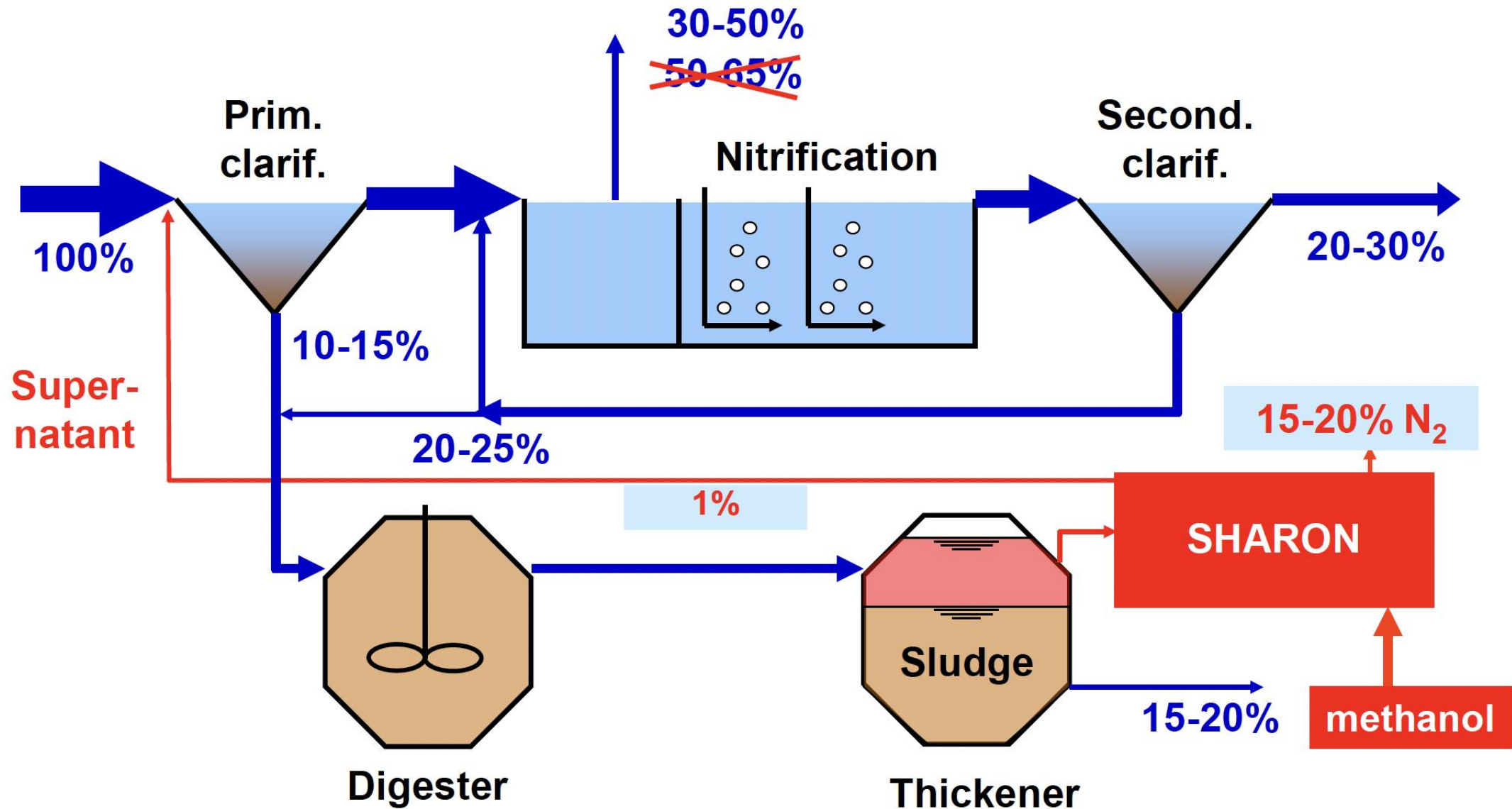
In these steady-state reactors, HRT corresponds closely to the growth rate of the microorganisms. If they can not keep up, cells will be washed out.



# Control of pH with aerobic-anoxic cycles



# N-flux in a WWTP with 70-80% N removal



# Nitratisation-

**This N removal process is most effective in:**

-sidestream treatment, including digestate centrate treatment

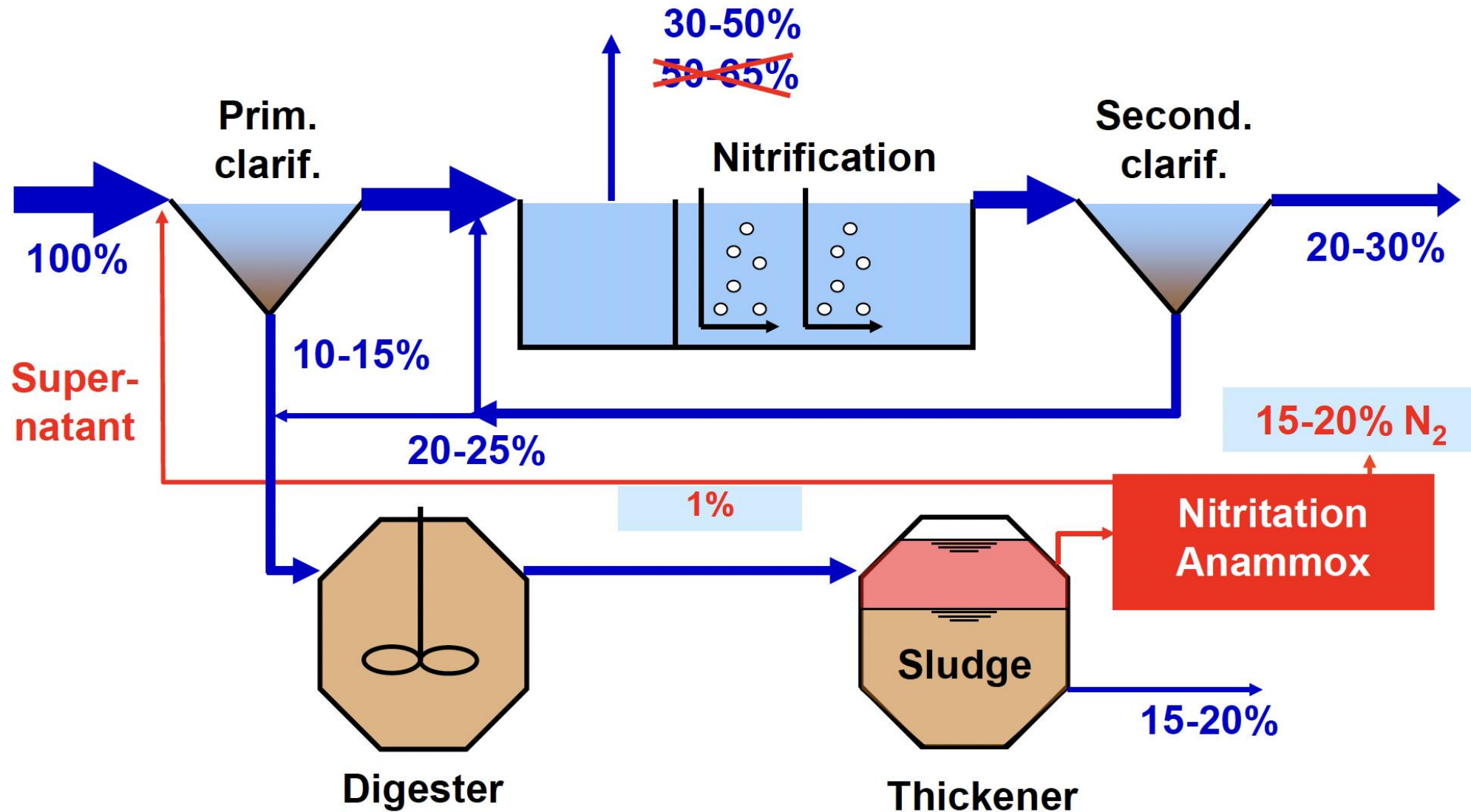
Because:

- Load fluctuations are smaller
- NOB washout easier
- Biomass retention high

Another advanced N treatment, without the need of carbon dosing:

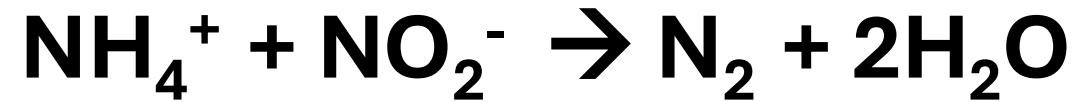
Combine nitrification+Anammox

# N-flux in a WWTP with 70-80% N removal



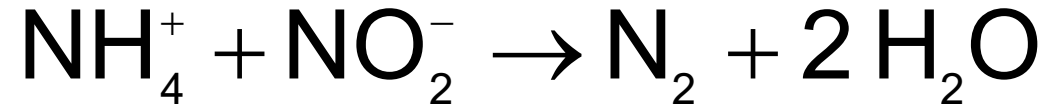
# ANAMMOX

## Anaerobic AMMonium OXidation

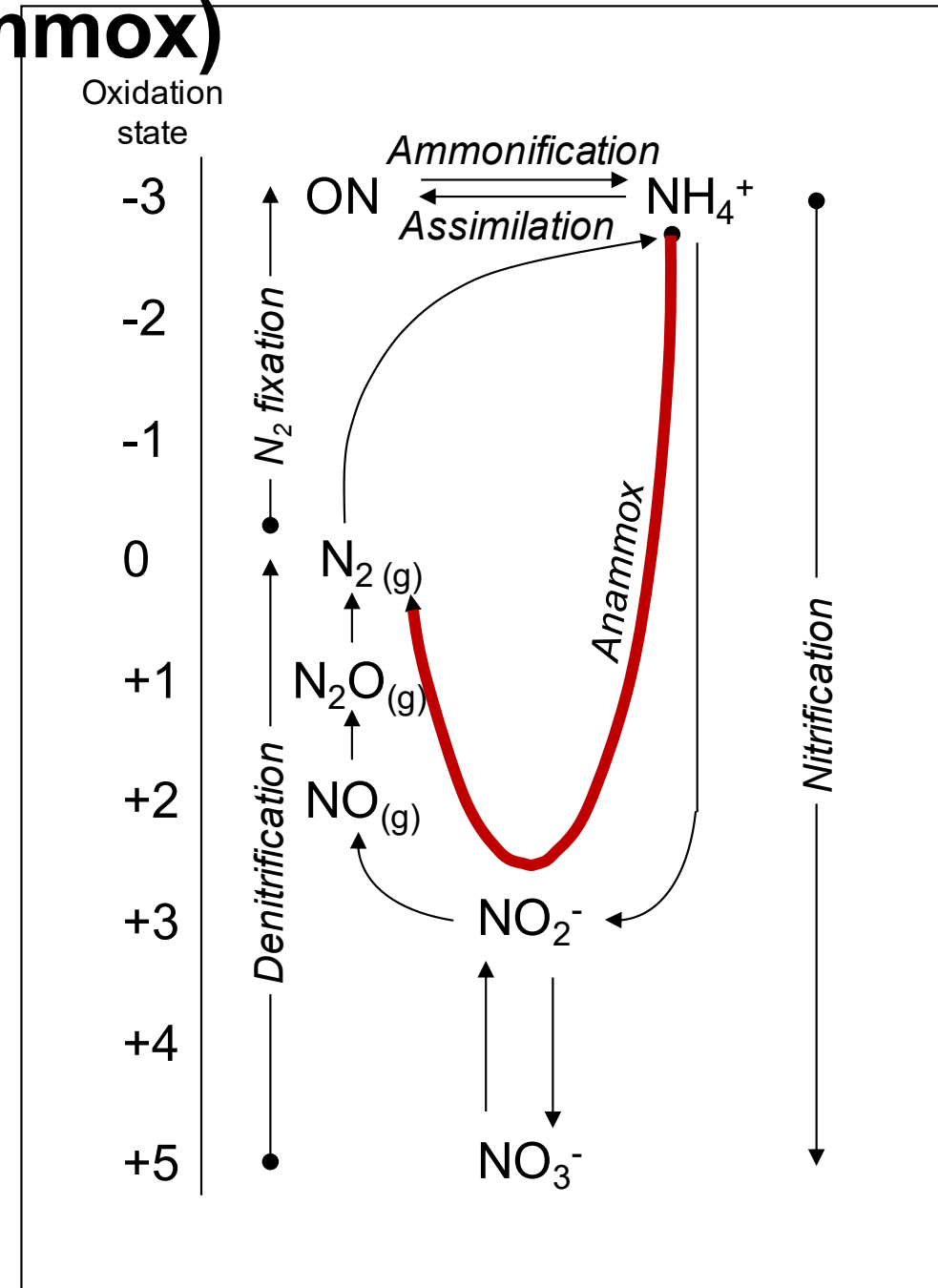


- strict anaerobes
- chemo-litho-autotroph
- extremely slow growth ( $t_d = 11$  d)
- low biomass yield

# Anaerobic Ammonia Oxidation (Anammox)



- Autotrophic, Chemolithotrophic, anaerobic
- Performed by unusual group of obligate anaerobic bacteria
- *Brocadia anammoxidans* is a *Planctomycetes* and a major anammox organism
  - *Planctomycetes* are unusual because their cytoplasm contains membrane-enclosed compartments
  - In *B. anammoxidans*, this is the anammoxosome, where anammox occurs



# Cell of ANAMMOX bacterium

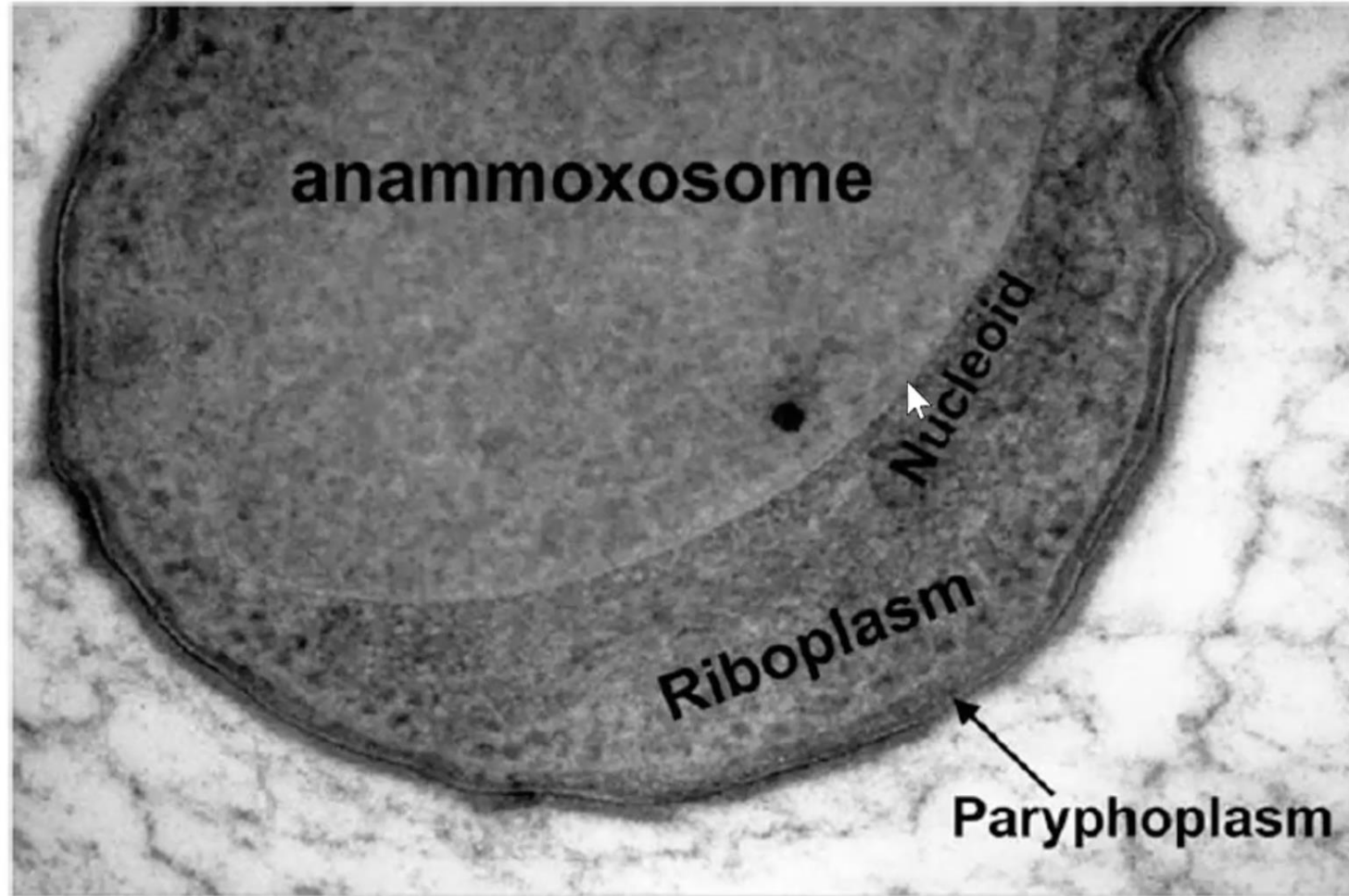


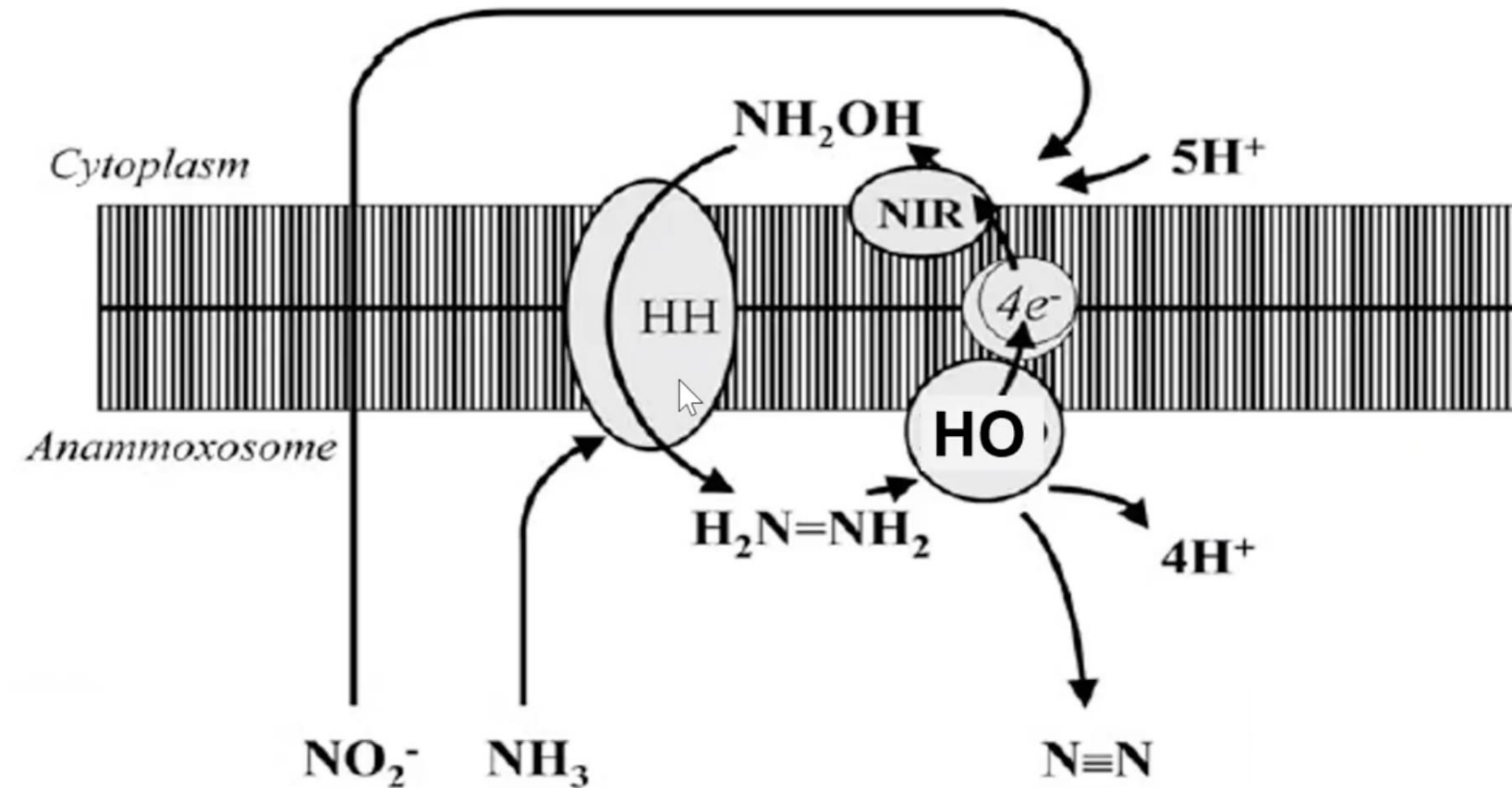
Figure 2. Electron micrograph of the planctomycete like anammox bacterium *Candidatus Brocadia anammoxidans*, showing typical compartmentalization. Internal compartment containing the enzyme hydroxylamine oxidoreductase, is named anammoxosome. The middle compartment containing the nucleoid and ribosomes is shown as riboplasm. The most outer compartment is named paryphoplasm (Lindsay et al. 2001).

# Proposed mechanism of anaerobic ammonium oxidation

- hydrazine ( $\text{N}_2\text{H}_4$ ) is a highly reactive, toxic, high-energy intermediate, anammox bacteria keep it inside the anammoxosome — a dedicated membrane-bound compartment — so it can be produced, and then oxidized in a controlled place that (a) protects the rest of the cell from poisoning and (b) lets the cell capture the energy safely.

Hydrazine is actually rocket fuel!

- Strict anaerobes
- Chemo-litho-autotroph
- Extremely slow growth ( $t_d = 11\text{d}$ )
- Low biomass yield



HH: hydrazine hydrolase  
 HO: hydrazine oxidoreductase  
 NIR: nitrite reductase

# Anammox Sequencing Batch Reactor (SBR)



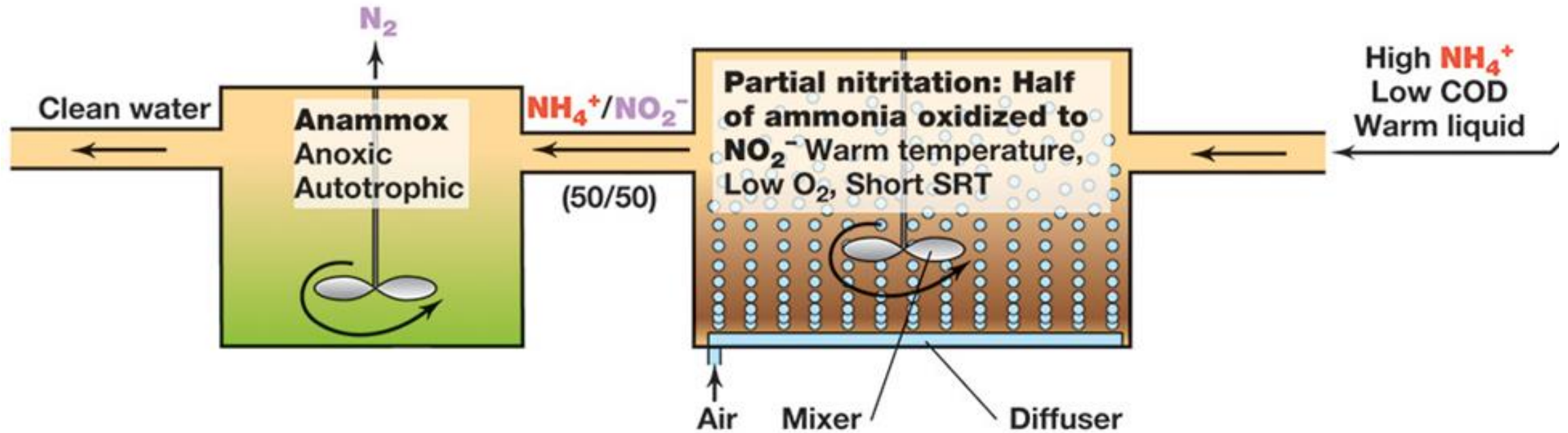
**Doubling time  
10-20 days**

**Enrichment  
120-200 days**

**70-80%  
Anammox  
bacteria**

**Red or brick-red color in an enriched anammox reactor comes mainly from the very high content of heme-containing cytochrome c proteins inside anammox bacteria.**

# Partial nitrification + Anammox (PNA) in WWTP

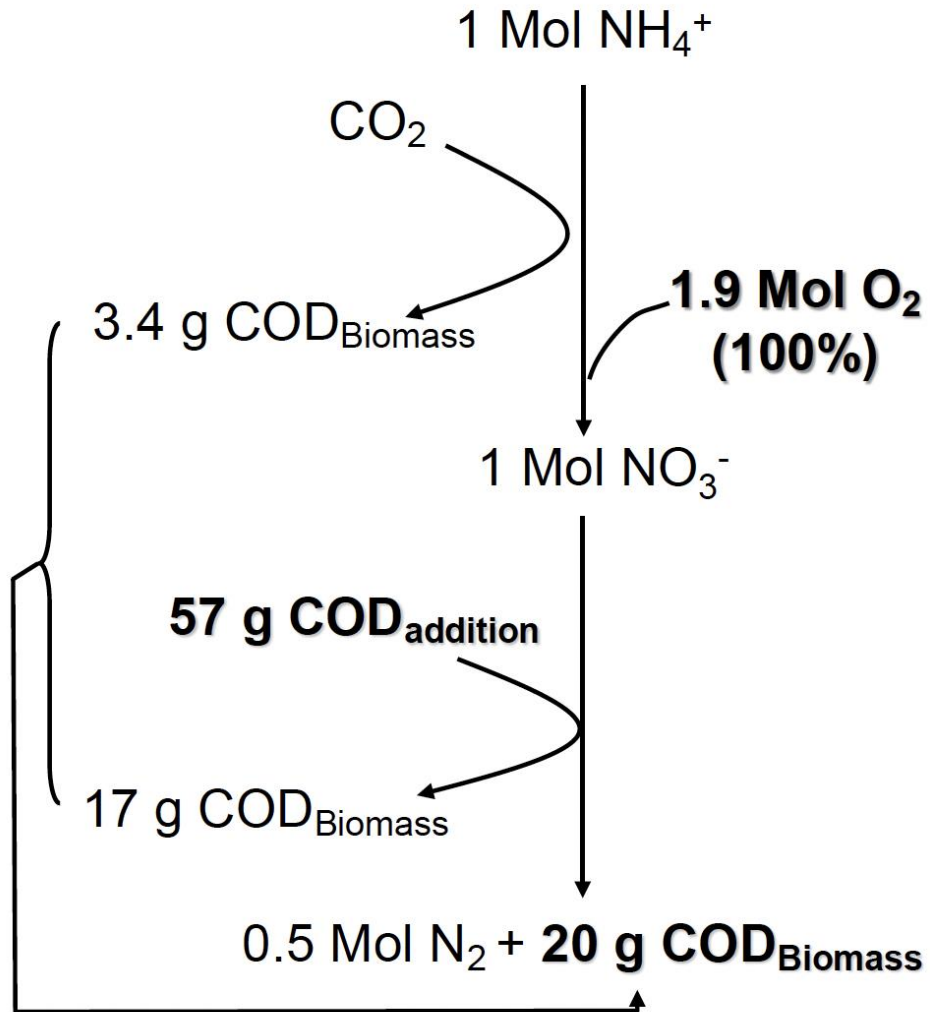


(d)

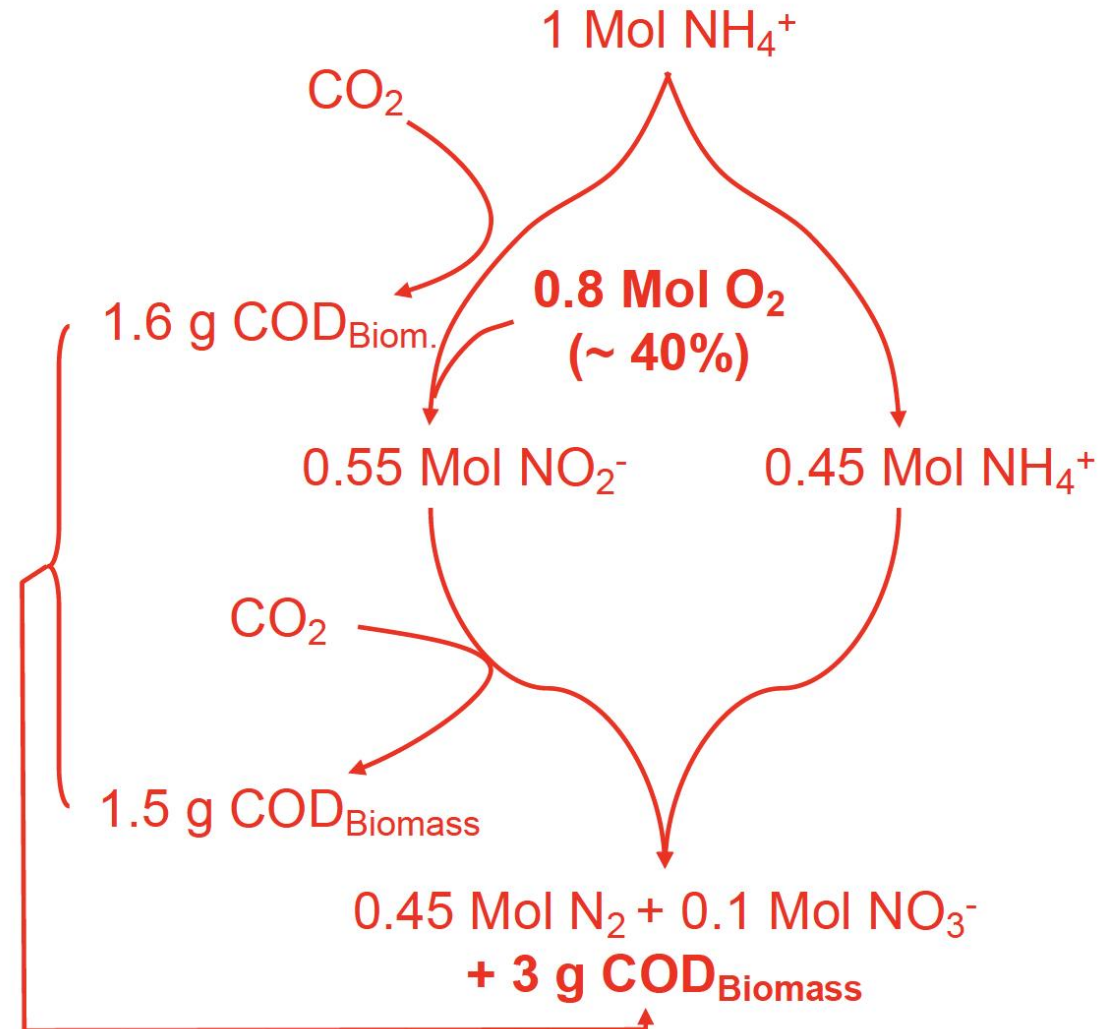
- No external carbon
- Low  $O_2$  requirement
- Less sludge
- Lower GHGs emission ( $N_2O$ )

# Comparison with conventional

## Nitrification + heterotrophic denitrification



## Partial nitrification + Anammox



# Process options

- **2 steps:** nitrification and anammox separate
  - Suspended solids
    - >> SHARON + Anammox
- **1 step:** nitrification/anammox combined
  - Biofilm reactor
    - >> ANITATMMox (MBBR technology, Véolia)
    - >> OLAND (Oxygen-Limited Autotrophic Nitrification-Denitrification)
  - Granular sludge
    - >> CANON (Completely Autotrophic Nitrogen-removal Over Nitrite)
  - Suspended solids
    - >> Eawag-process (Zürich-Werdhölzli, St. Gallen, Niederglatt)
    - >> DEMON (Bilten, Thun)

## Microbial competition:

why can't we use this process for the mainstream N removal?

### 1. In sidestream anammox reactors (centrate): **OUTCOMPETITION** is rare

- Sidestream conditions strongly favor anammox:
- **High  $\text{NH}_4^+$  (~1000–2000 mg/L)**
- **Low COD (very little organic carbon)**
- **Warm (30–35°C)**
- **Controlled nitritation (partial nitrification)**
- Here, heterotrophic denitrifiers cannot grow much due to carbon limitation, and NOB are suppressed by process control. **Result: Anammox outcompetes heterotrophs easily.**
- Sidestream anammox is considered a *mature and stable* technology.

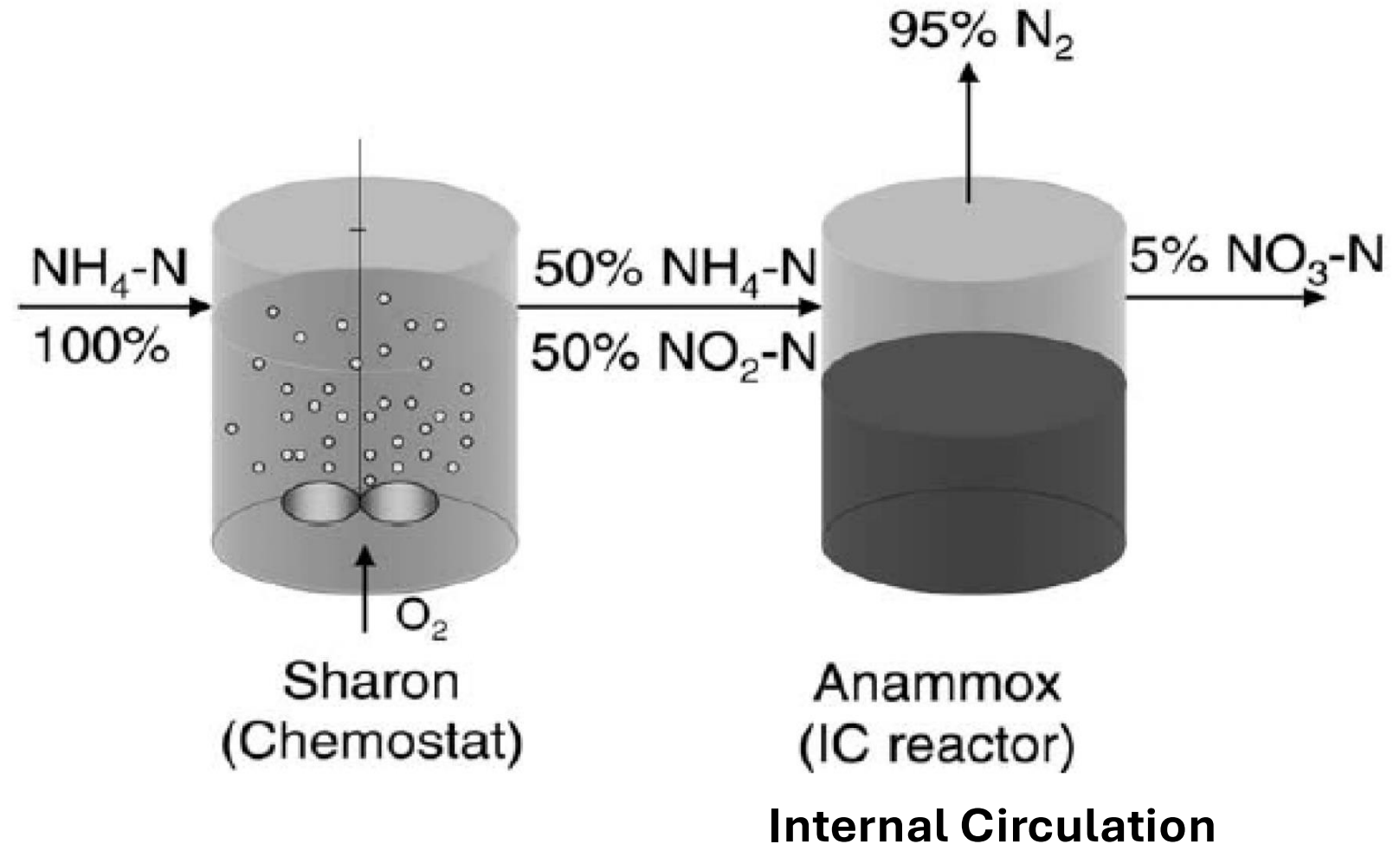
### 2. In mainstream municipal wastewater: **competition!**

- Lower ammonia (20–50 mg N/L)
- Higher COD
- Cooler temperatures (10–20°C)
- More biomass diversity

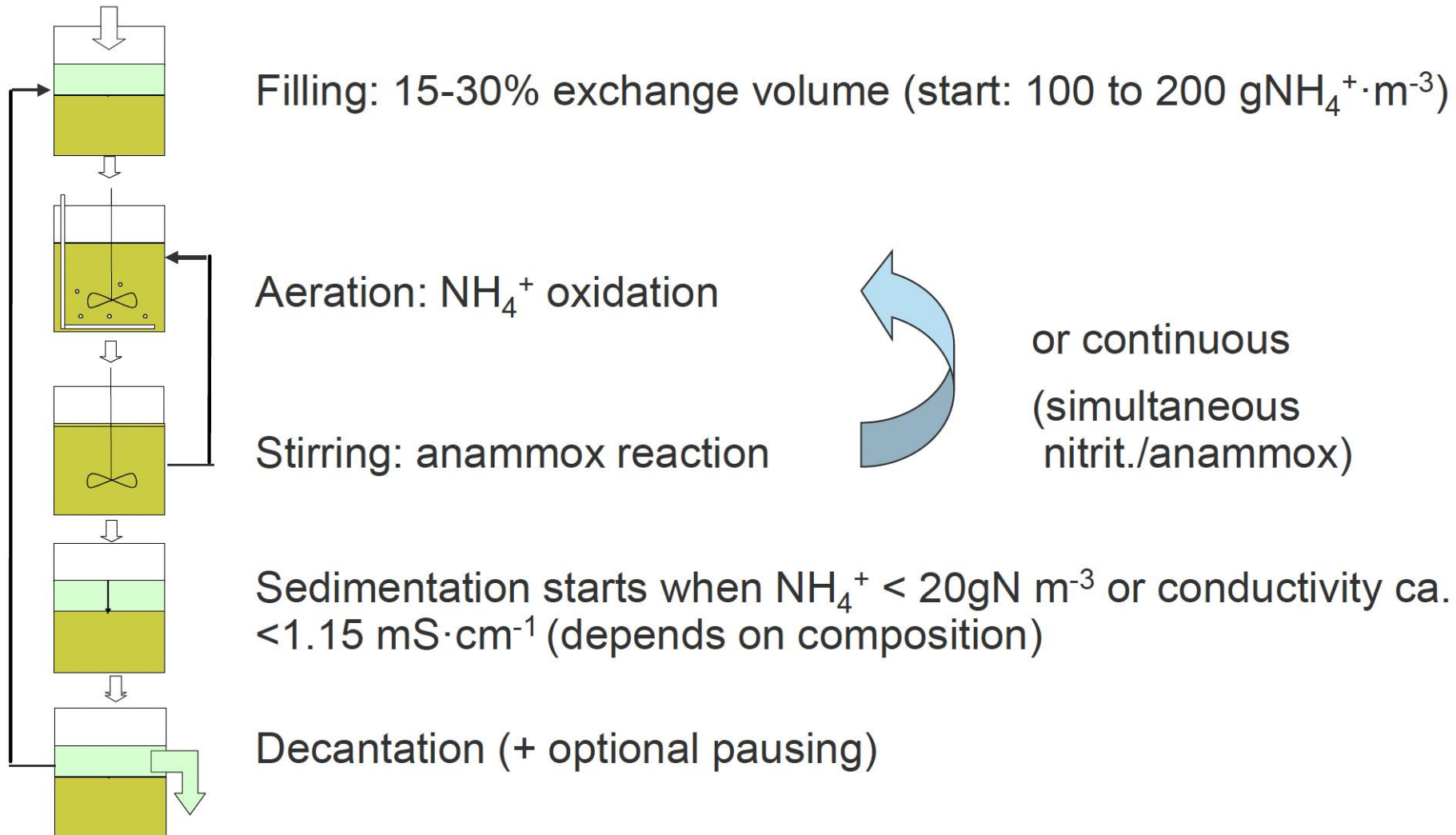
These conditions favor:

**Heterotrophs and NOB grow much faster, they can outcompete anammox if not well-controlled.**

# Combined SHARON-ANAMMOX process for the removal of ammonium from sludge digestion effluents



# 1 step Eawag nitrification/anammox SBR process: SBR cycle, typically 6 to 10 h



# 1 step Eawag nitritation/anammox SBR process: Critical control parameter



<20 gNH<sub>4</sub><sup>+</sup>-N·m<sup>-3</sup>: end of aeration, start sedimentation



Accumulation (>5 mgNO<sub>2</sub><sup>-</sup>-N/L) = O<sub>2</sub> supply too high (=NOB growth!)

Automatic supervision at every batch improves reliability

Toxicity limit >100 gNO<sub>2</sub><sup>-</sup>-N·m<sup>-3</sup>



Normal: ≤10% of NH<sub>4</sub><sup>+</sup> → NO<sub>3</sub><sup>-</sup> (Anammox)

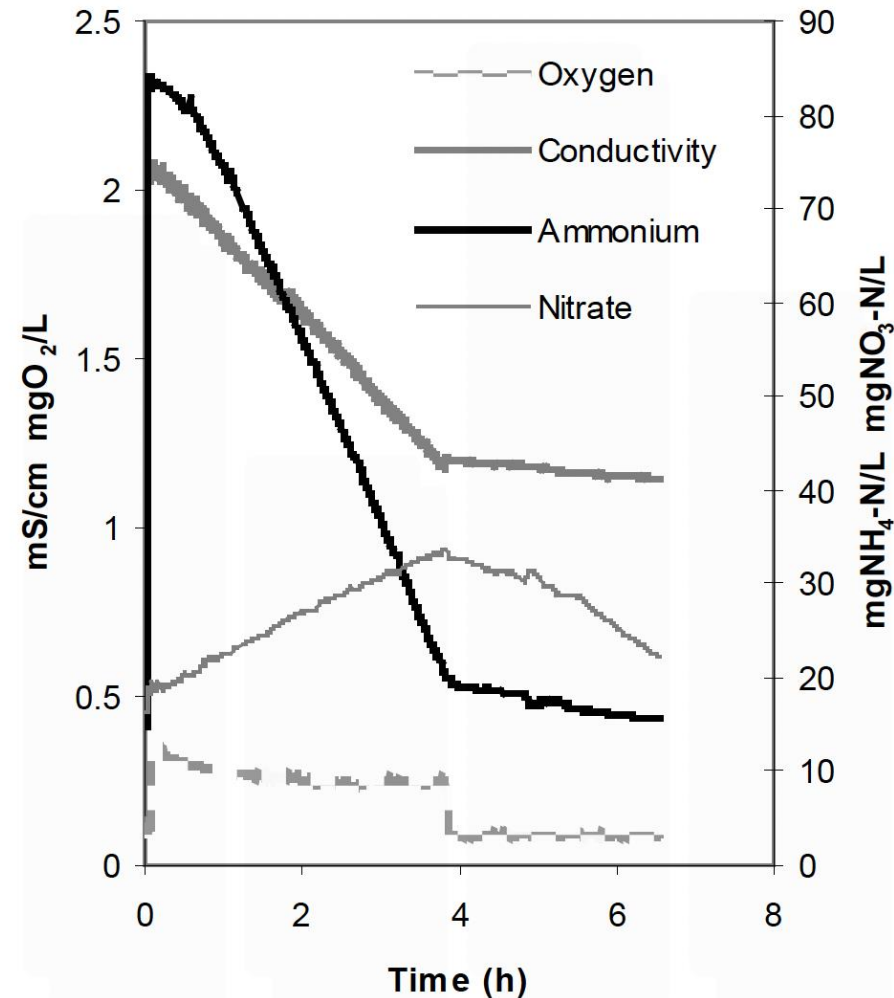
>20%: Nitrite oxidizing bacterien (NOB) are growing



Normal: 0.2 – 0.6 mgO<sub>2</sub>·L<sup>-1</sup>

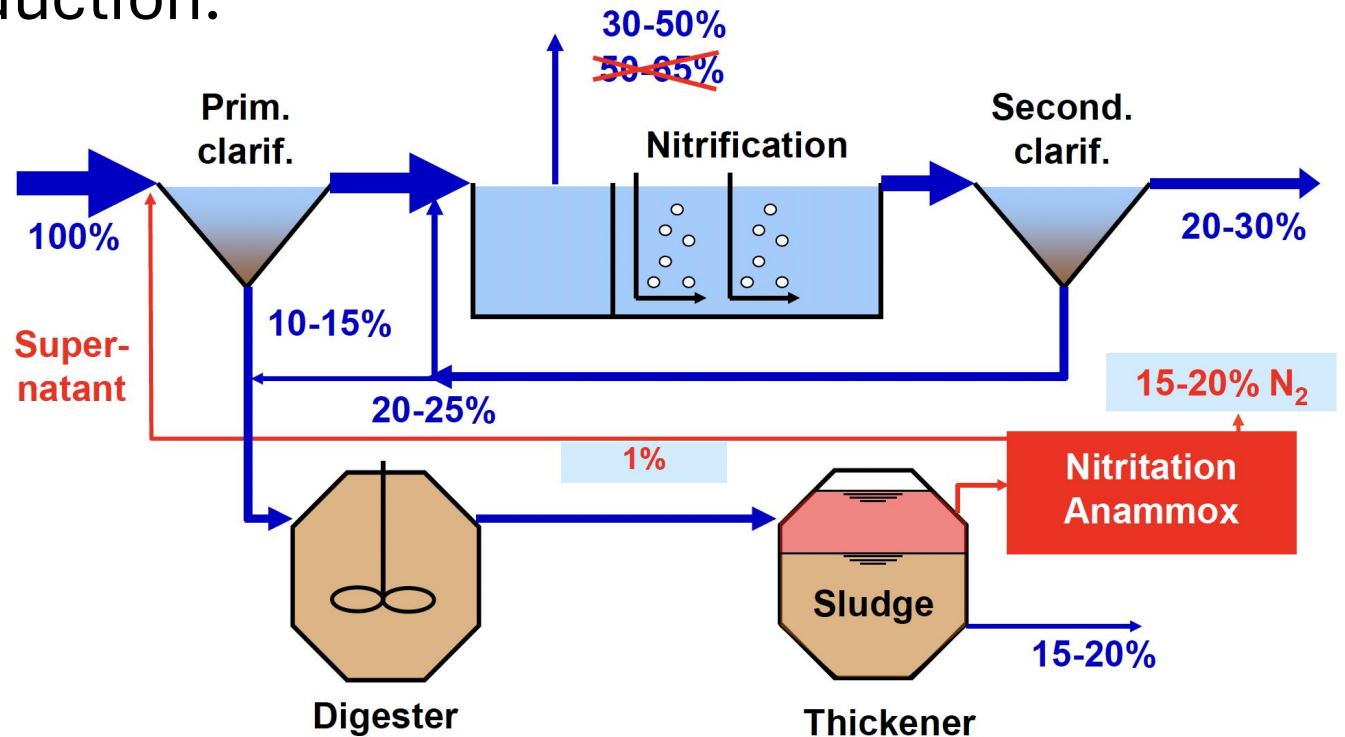
≥1 mgO<sub>2</sub>·L<sup>-1</sup> : aeration emergency shut off

Aeration control: by volume not O<sub>2</sub> concentration

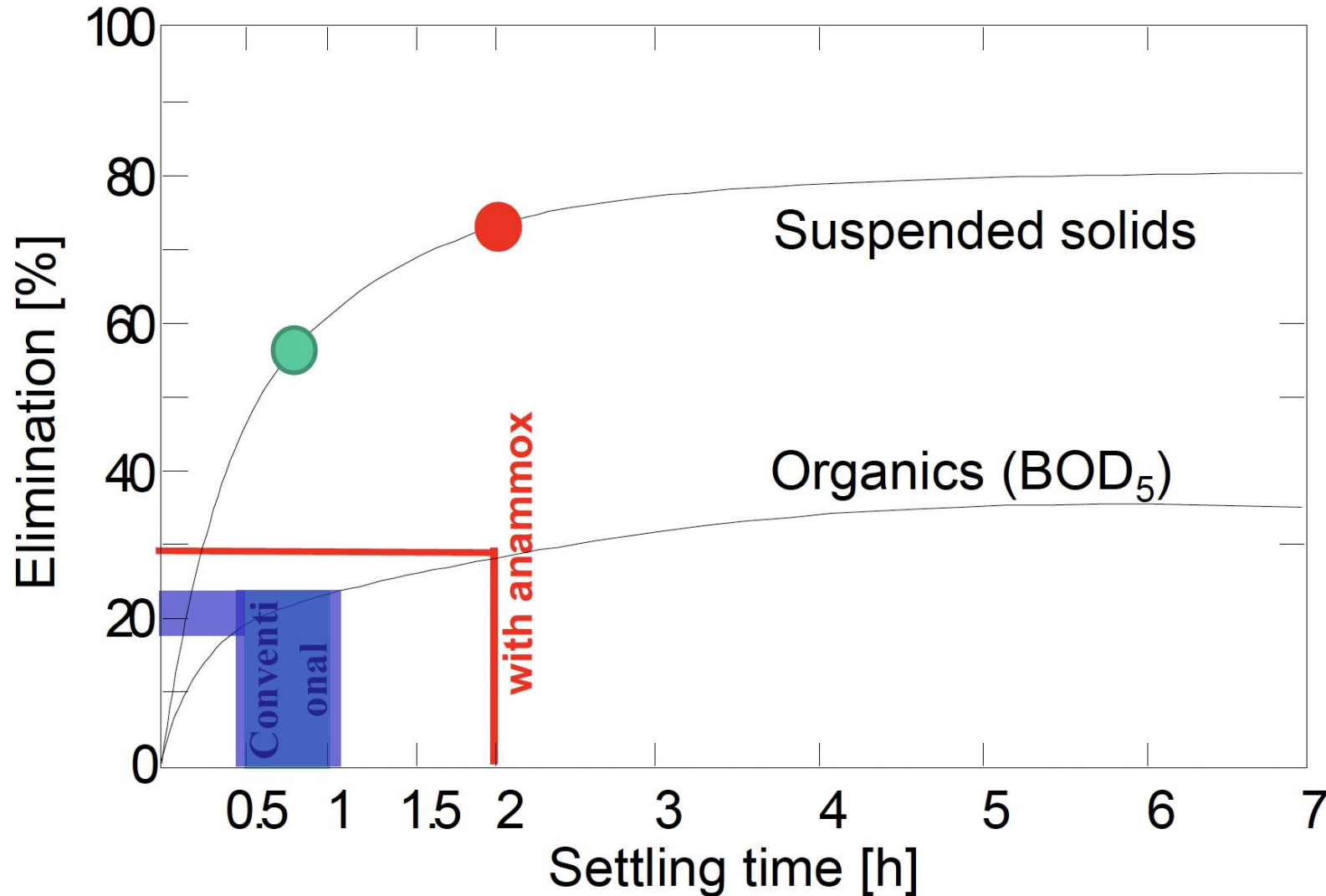


# Whole system adjustment following sidestream treatment

- With the upgrade of sidestream treatment, we removed much more N there than initially planned (that goes back into inflow), then less organic matter is consumed for denitrification, but convert to activated sludges, ultimately bring more suspended solids into anaerobic digestion to increase biogas production.



# Anammox allows increased BOD-removal during primary clarification



Increase the settling time to increase elimination percentage, diverting more SS (up to 70%) /BOD<sub>5</sub> to Digestion.

But need to make a bigger Primary clarifier footprint.

# Assumptions for COD + N-flux per person and day

## Average influent load

110 gCOD p<sup>-1</sup>d<sup>-1</sup>

10 gN p<sup>-1</sup> d<sup>-1</sup>

## Digested sludge

35 gCOD p<sup>-1</sup>d<sup>-1</sup>

1.5 gN p<sup>-1</sup> d<sup>-1</sup>

## Effluent load

5 gCOD p<sup>-1</sup>d<sup>-1</sup>

2.5 gNO<sub>3</sub>-N p<sup>-1</sup>d<sup>-1</sup>

## HRT of primary settler

Case a) 0.5-1 h:

Case b) 2 h + flocculant:

## BOD ≈ COD removal

20-25% (ATV Handbook)

~ 40% (Sandino, Wat.21)

## N-removal

10%: 1.0 gN p<sup>-1</sup>d<sup>-1</sup>

15%: 1.5 gN p<sup>-1</sup>d<sup>-1</sup>

## Biomass (0.05 gN gCOD<sup>-1</sup>)

45-50% of eliminated COD

Case a) 40 gCOD p<sup>-1</sup>d<sup>-1</sup>, 2.0 gN p<sup>-1</sup>d<sup>-1</sup>

Case b) 30 gCOD p<sup>-1</sup>d<sup>-1</sup>, 1.5 gN p<sup>-1</sup>d<sup>-1</sup>

## Denitrification efficiency

50-60% of N in primary effluent

6.0 gN p<sup>-1</sup>d<sup>-1</sup>

4.5 gN p<sup>-1</sup>d<sup>-1</sup>

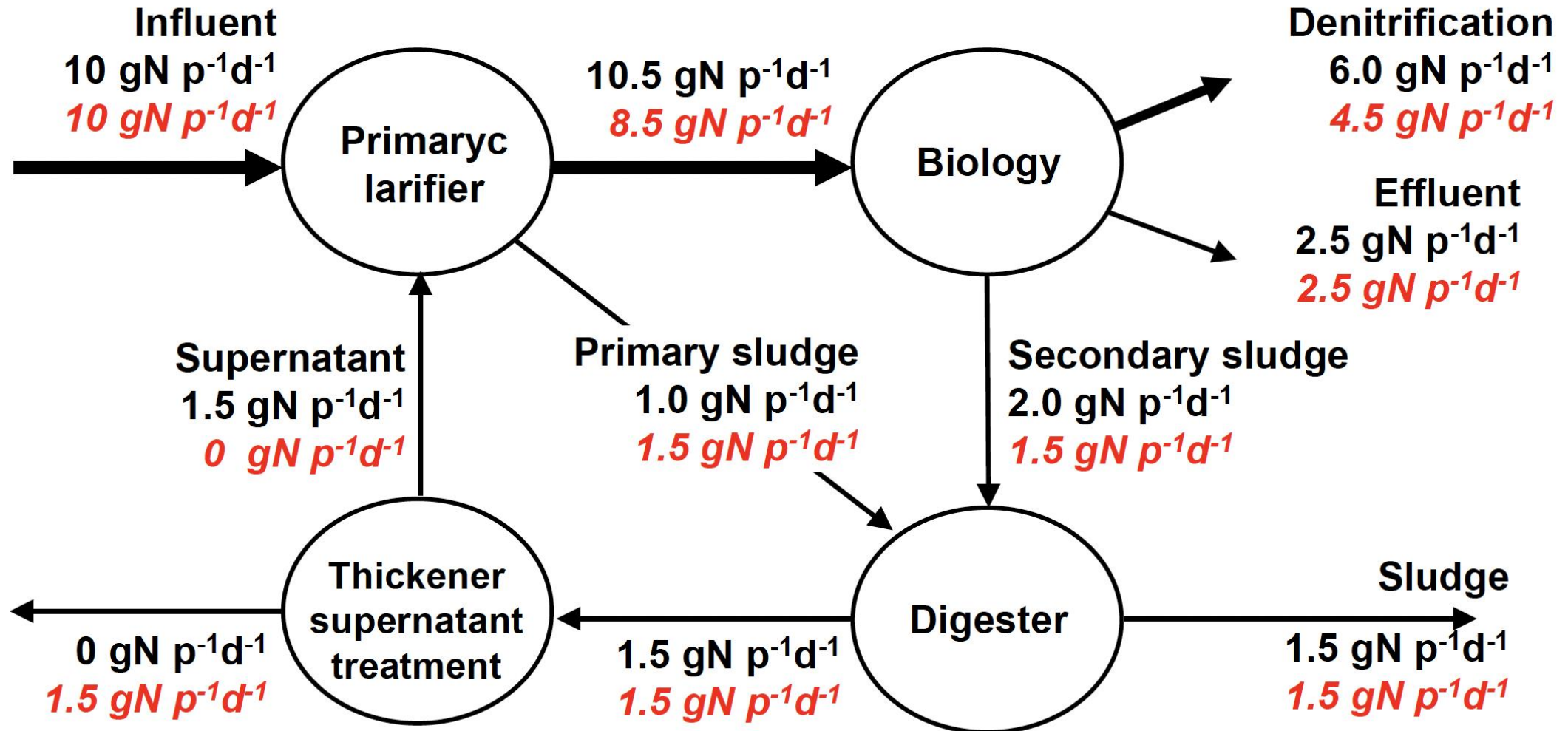
## Digester liquid treatment in combination with case b:

95% N-removal = 1.5 gN p<sup>-1</sup>d<sup>-1</sup>

# N flux per person and day

a) Primary clarification with 0.5–1 h

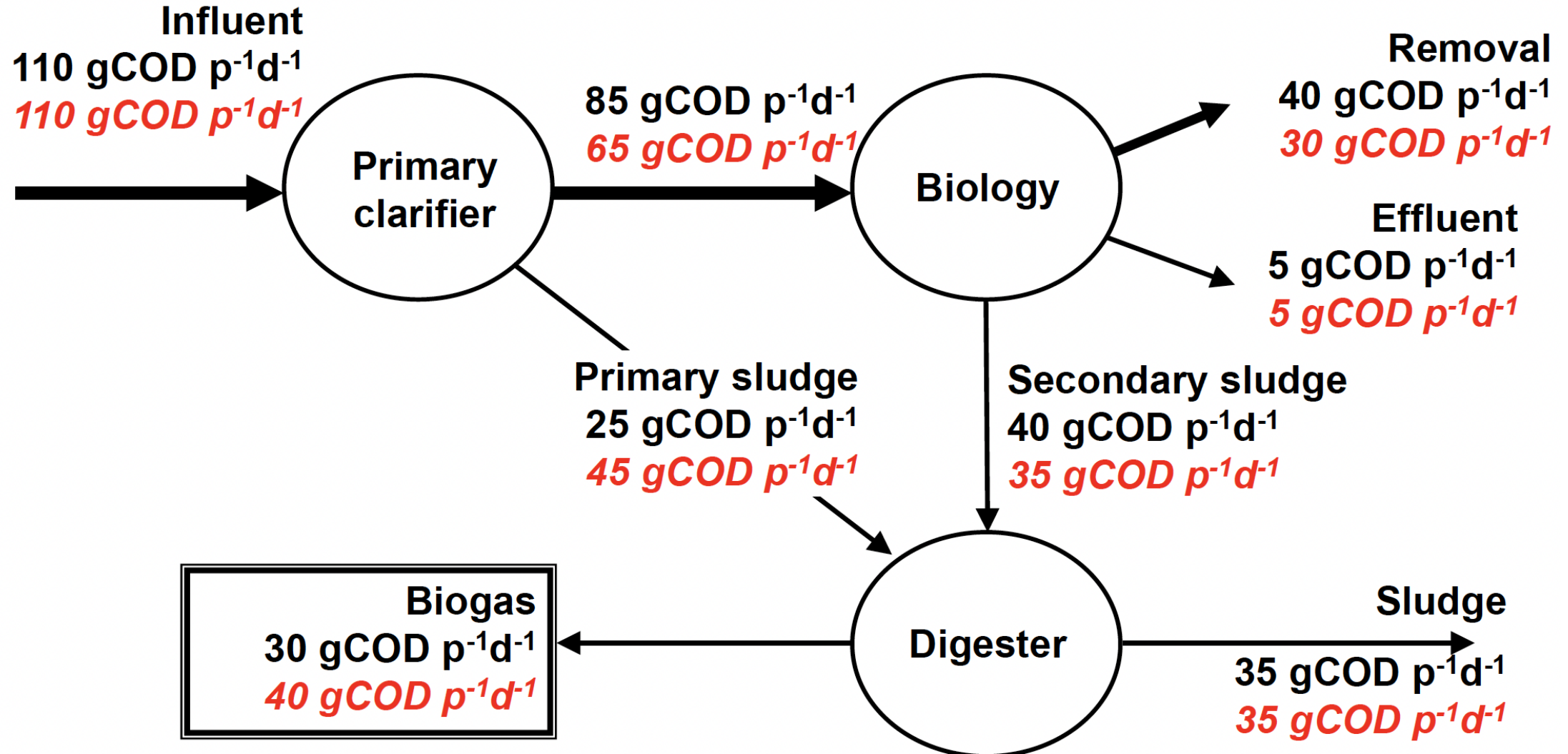
*b) Primary clarification with 2 h, flocculation + supernatant treatment*



# COD flux per person and day

a) Primary clarification with 0.5–1 h

*b) Primary clarification with 2 h, flocculation + supernatant treatment*



# Assumptions for electrical energy balance

**Electrical energy consumption for aeration:**

**1.0 kWh per kgO<sub>2</sub> consumed,**

1.0 kgO<sub>2</sub>-consumption per kgCOD degraded

4.6 kgO<sub>2</sub>-consumption per kgNH<sub>4</sub><sup>+</sup>-N oxidized to NO<sub>3</sub><sup>-</sup>

1.7 kgO<sub>2</sub>-consumption per kgNH<sub>4</sub><sup>+</sup>-N oxidized to N<sub>2</sub>

Inlet nitrogen is only in the oxidation state of NH<sub>4</sub><sup>+</sup>

**Electrical energy consumption for**

**pumping and mixing      0.02 kWh p<sup>-1</sup> d<sup>-1</sup>**

**Electrical energy from biogas:**

14 MJ kgCOD<sup>-1</sup> = 3.9 kWh kgCOD<sup>-1</sup>, 33% electrical energy:

**1.3 kWh kgCOD<sup>-1</sup>**

# Energy consumption per person and day

a) Primary clarification with 0.5–1 h

*b) Primary clarification with 2 h, flocculation + supernatant treatment*

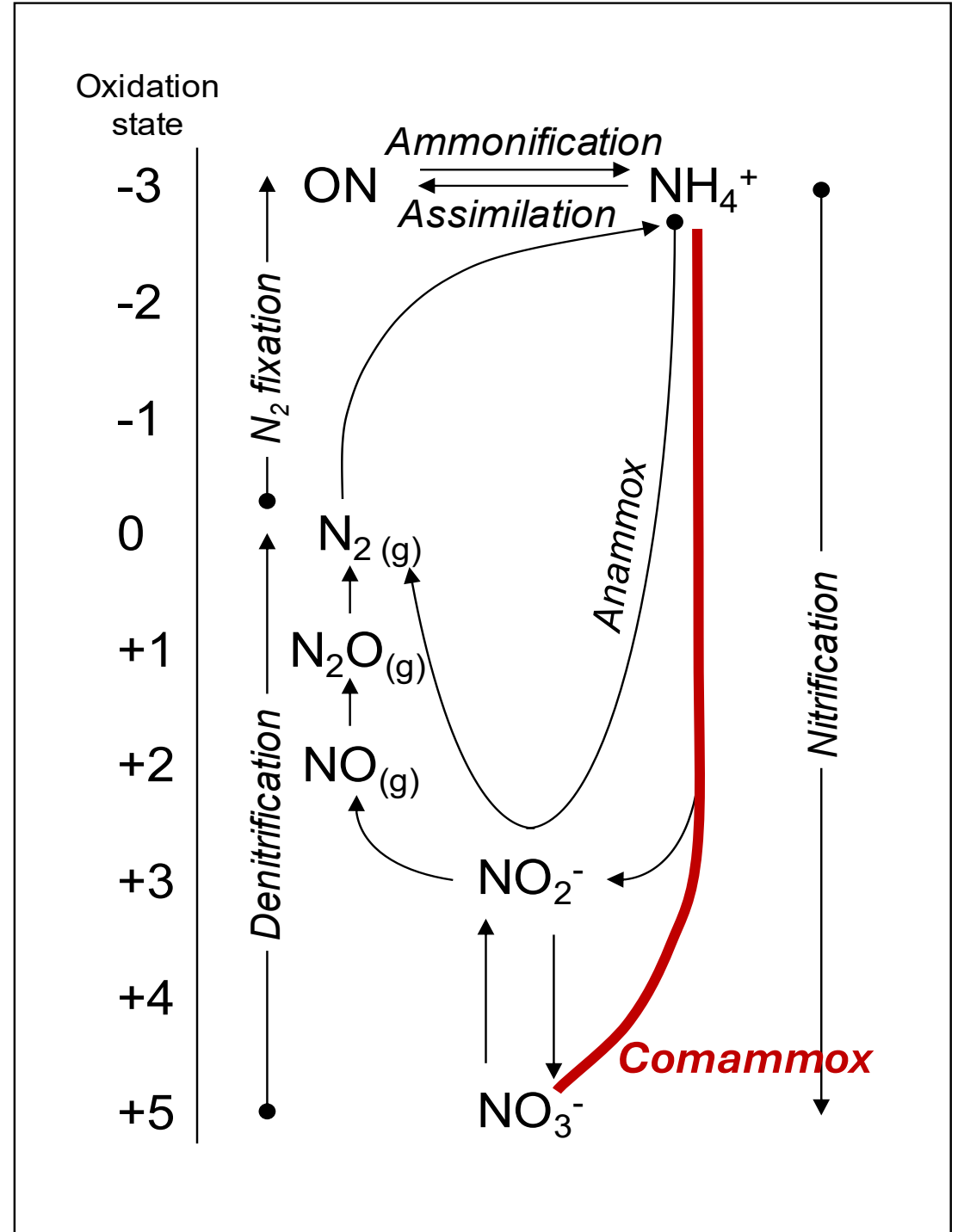
Electricity aeration (incl. supernatant)	gO <sub>2</sub> p <sup>-1</sup> d <sup>-1</sup>	kWh p <sup>-1</sup> d <sup>-1</sup>
COD removal	40	0.040
	<i>30</i>	<i>0.030</i>
Nitrification/Denitrification	22	0.022
	<i>22</i>	<i>0.022</i>
Electricity for pumping, stirring		0.020
		<i>0.020</i>
Electricity from biogas	gCOD·p <sup>-1</sup> d <sup>-1</sup>	
	-30	-0.038
	<i>-40</i>	<i>-0.051</i>
<hr/>		
Net electricity demand		0.044
		<i>0.021</i>
Option: co-substrates (e.g. WWTP Zürich)		<i>0.009</i>

Additional N metabolism microorganisms:

Not used in practice yet, but this type of bacteria co-exist with nitrifiers, especially in attached growth

# Comammox

- Comammox can oxidize  $\text{NH}_3$  completely to  $\text{NO}_3^-$



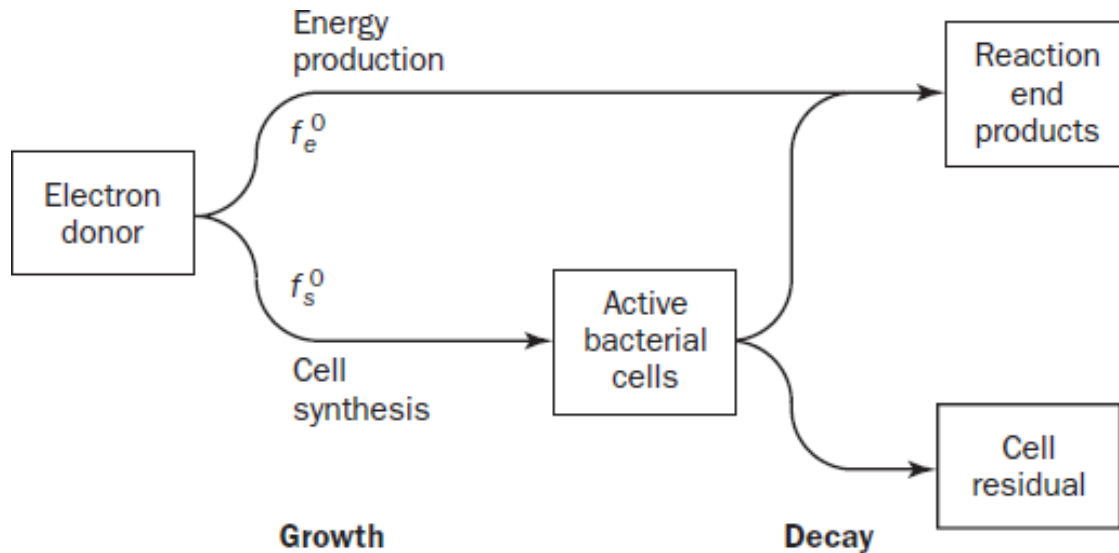
Microbial Group	Electron Donor	Electron Acceptor	Carbon Source Type	Relative Growth Rate	Biomass Yield
<b>AOB, AOA</b> (Ammonia-Oxidizing Bacteria)	$\text{NH}_3/\text{NH}_4^+$	$\text{O}_2$	Autotrophic ( $\text{CO}_2$ )	<b>Slow</b>	<b>Low</b>
<b>NOB</b> (Nitrite-Oxidizing Bacteria)	$\text{NO}_2^-$	$\text{O}_2$	Autotrophic ( $\text{CO}_2$ )	<b>Moderate (faster than AOB)</b>	<b>Low</b>
<b>Denitrifiers</b>	Organic carbon (COD, VFAs, methanol)	$\text{NO}_3^-$ or $\text{NO}_2^-$	Heterotrophic (Organic C)	<b>Fast</b>	<b>High</b>
<b>Anammox</b> bacteria	$\text{NH}_4^+$	$\text{NO}_2^-$	Autotrophic ( $\text{CO}_2$ )	<b>Very slow</b>	<b>Very low</b>
<b>Comammox</b> bacteria	$\text{NH}_4^+$	$\text{O}_2$	Autotrophic ( $\text{CO}_2$ )	<b>Slowest among nitrifiers</b>	<b>Very low</b>



# IWA Activated Sludge Model for Complex Systems

Approach	Where it is Used	Role of IWA ASM Models
Simplified Numbers (Hand Calculations)	Preliminary design, screening of alternatives, rough sizing of tanks, quick checks, and regulatory reports.	Used to determine basic parameters like HRT and SRT and to check simple mass balances for primary flow.
IWA ASM-Type Models	Final design, complex nutrient removal (N and P) process optimization, dynamic analysis, and troubleshooting of existing plants.	These are the core mechanistic models (e.g., ASM1, ASM2, ASM 3) integrated into commercial software such as BioWin, GPS-X, WEST.

# Traditional Decay Model



**Table 5.1** Process Kinetics and Stoichiometry for Aerobic Growth of Heterotrophic Bacteria. Traditional Model for Biomass Decay

Process	Component <sup>a</sup>				Process rate, $r_j$
	$X_{B,H}$	$X_D$	$S_s$	$S_O^b$	
Growth	1		$-(1/Y_H)$	$\left(\frac{1 - Y_H}{Y_H}\right)$	$\mu_H \cdot X_{B,H}$
Decay	-1	$f_D$		$(1 - f_D)$	$b_H \cdot X_{B,H}$

<sup>a</sup>All components and coefficients are expressed as COD.

<sup>b</sup>Coefficients must be multiplied by  $-1$  to express them as oxygen.

Net rate of biomass growth:

$$r_{XB} = \mu_H X_{B,H} - b_H X_{B,H}$$

Rate of biomass debris generation:

$$r_{XD} = b_H f_D X_{B,H}$$

Rate of soluble substrate consumption:

$$r_{SS} = -\left(\frac{\mu_H}{Y_H}\right) X_{B,H}$$

Rate of  $O_2$  consumption (in COD units):

$$r_{SO} = \left(\frac{1 - Y_H}{Y_H}\right) \mu_H X_{B,H} + (1 - f_D) b_H X_{B,H}$$

# IWA Activated Sludge Models

(IWA=International Water Association)

The IWA AS models (ASMs) are mathematical models that were developed to better integrate multiple events in bioreactors

- ✓ IWA ASM No. 1
  - o carbon oxidation, nitrification, denitrification
- ✓ IWA ASM No. 2
  - o ASM No. 1 + biological phosphorus removal
- ✓ IWA ASM No. 2d
  - o Assumes denitrifying bacteria store polyphosphate
- ✓ IWA ASM No. 3
  - o Adjusts some assumptions from ASM No. 2d.
  - o organic substrate stored intracellularly before degradation

# IWA ASMs Consider Slowly Biodegradable Substrate

<b>Component</b>	<b>Concentration</b>
Inert particulate organic matter	35 mg/L as COD
Slowly biodegradable substrate	150 mg/L as COD
Readily biodegradable substrate	115 mg/L as COD
Oxygen	0 mg/L as O <sub>2</sub>
Soluble nitrate-N	0 mg/L as N
Soluble ammonia-N	25 mg/L as N
Soluble biodegradable organic N	6.5 mg/L as N
Particulate biodegradable organic N	8.5 mg/L as N
Alkalinity	5 mM

# IWA Models are interactive

assumes multiple complementary nutrients can influence  $\mu$  simultaneously  
 complementary nutrients = nutrients that satisfy different growth needs

**Table 6.1** Process Kinetics and Stoichiometry for Multiple Events in Suspended Growth Cultures as Presented by IWA Task Group on Mathematical Modeling for ASM1

Component <sup>a</sup> → i	1	2	3	4	5	6	7	8	9	10	11	12	13	Process rate, $r_j$ , $\text{ML}^{-3}\text{T}^{-1}$
j   Process ↓	$X_I$	$X_S$	$X_{B,H}$	$X_{B,A}$	$X_D$	$S_I$	$S_S$	$S_O^b$	$S_{NO}$	$S_{NH}$	$S_{NS}$	$X_{NS}$	$S_{ALK}$	
1   Aerobic growth of heterotrophs			1				$-\frac{1}{Y_H}$	$\frac{1-Y_H}{Y_H}$		$-i_{N/XB}$			$-\frac{i_{N/XB}}{14}$	$\hat{\mu}_H \left( \frac{S_S}{K_S + S_S} \right) \left( \frac{S_O}{K_{O,H} + S_O} \right) X_{B,H}$
2   Anoxic growth of heterotrophs			1				$-\frac{1}{Y_H}$		$-\frac{1-Y_H}{2.86Y_H}$	$-i_{N/XB}$			$\frac{1-Y_H}{14(2.86Y_H)} - \frac{i_{N/XB}}{14}$	$\hat{\mu}_H \left( \frac{S_S}{K_S + S_S} \right) \left( \frac{K_{O,H}}{K_{O,H} + S_O} \right) \left( \frac{S_{NO}}{K_{NO} + S_{NO}} \right) \eta_e X_{B,H}$
3   Aerobic growth of autotrophs				1				$\frac{4.57 - Y_A}{Y_A}$	$\frac{1}{Y_A}$	$-i_{N/XB} - \frac{1}{Y_A}$			$-\frac{i_{N/XB}}{14} - \frac{1}{7Y_A}$	$\hat{\mu}_A \left( \frac{S_{NH}}{K_{NH} + S_{NH}} \right) \left( \frac{S_O}{K_{O,A} + S_O} \right) X_{B,A}$
4   Death and lysis of heterotrophs		$1 - f'_D$	-1		$f'_D$							$i_{N/XB} - f'_D i_{N/XD}$		$b_{L,H} X_{B,H}$
5   Death and lysis of autotrophs		$1 - f'_D$		-1	$f'_D$							$i_{N/XB} - f'_D i_{N/XD}$		$b_{L,A} X_{B,A}$
6   Ammonification of soluble organic nitrogen										1	-1		$\frac{1}{14}$	$k_a S_{NS} X_{B,H}$
7   "Hydrolysis" of particulate organics		-1					1							$k_h \frac{X_S/X_{B,H}}{K_X + (X_S/X_{B,H})} \left[ \left( \frac{S_O}{K_{O,H} + S_O} \right) + \eta_h \left( \frac{K_{O,H}}{K_{O,H} + S_O} \right) \left( \frac{S_{NO}}{K_{NO} + S_{NO}} \right) \right] X_{B,H}$
8   "Hydrolysis" of particulate organic nitrogen											1	-1		$r_7 (X_{NS}/X_S)$
Observed conversion rates, $\text{ML}^{-3}\text{T}^{-1}$	$r_i = \sum_{j=1}^n \Psi_{ij} r_j$													

---

**TABLE 6.2**  
**Definitions of Component Symbols in Table 6.1**

<b>Component Number</b>	<b>Component Symbol</b>	<b>Definition</b>
1	$X_I$	Inert particulate organic matter, mg/L as COD
2	$X_S$	Slowly biodegradable substrate, mg/L as COD
3	$X_{B,H}$	Active heterotrophic biomass, mg/L as COD
4	$X_{B,A}$	Active autotrophic biomass, mg/L as COD
5	$X_D$	Debris from biomass death and lysis, mg/L as COD
6	$S_I$	Inert soluble organic matter, mg/L as COD
7	$S_S$	Readily biodegradable substrate, mg/L as COD
8	$S_O$	Oxygen, mg/L as COD
9	$S_{NO}$	Nitrate nitrogen, mg/L as N
10	$S_{NH}$	Ammonia nitrogen, mg/L as N
11	$S_{NS}$	Soluble biodegradable organic nitrogen, mg/L as N
12	$X_{NS}$	Particulate biodegradable organic nitrogen, mg/L as N
13	$S_{ALK}$	Alkalinity, molar units

---

- The IWA ASM models were developed for suspended growth systems (conventional Activated Sludge). However, they can be extended to model attached growth and hybrid systems with some success.
- A separate biofilm sub-model is added to the overall simulation, which handles the physical limitations of mass transfer.

## **George Ekama's 5 Cautions Regarding Use of the IWA Model**

- Do not fall in love with your model.
- Do not try to adapt reality to your model
- Do not extrapolate models into areas where the model is not valid
- Do not tamper with kinetic and stoichiometric constants unless you know what you are doing
- Be sure you know what your goal is with the model