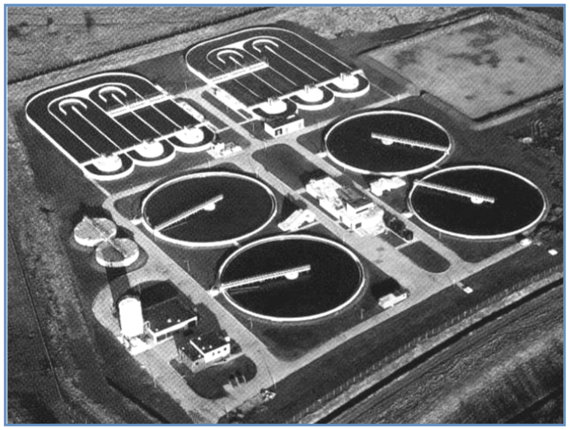
Lecture Aerobic granular sludge

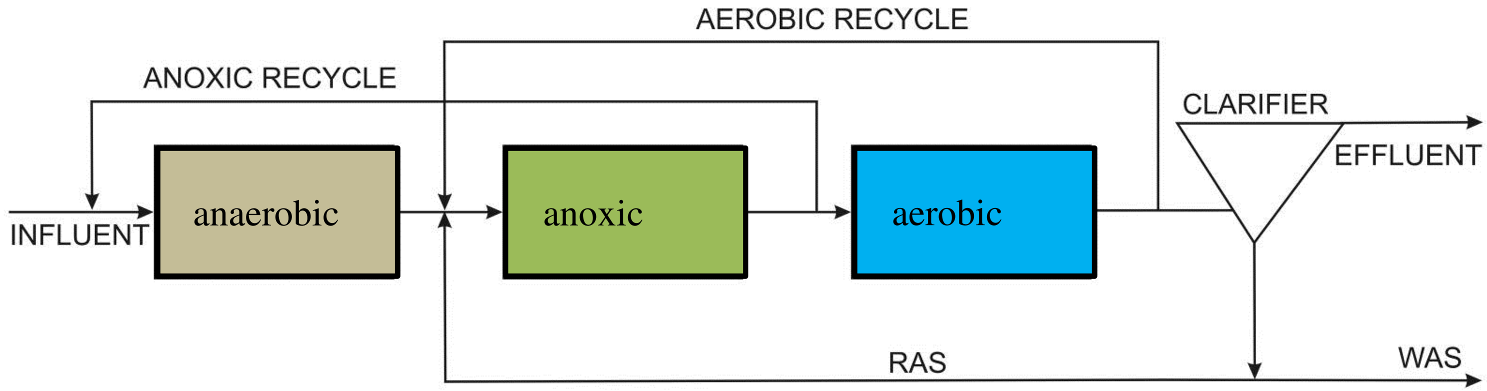
Mari Winkler

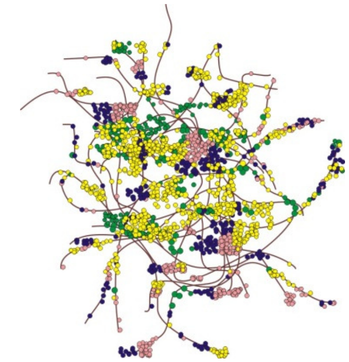
Conventional Activated Sludge system is widely used BUT……



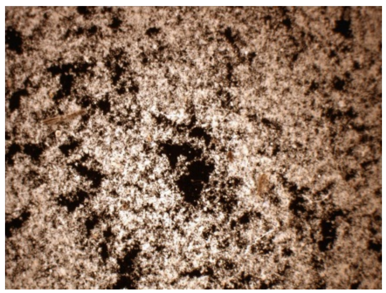



Treatment with flocs

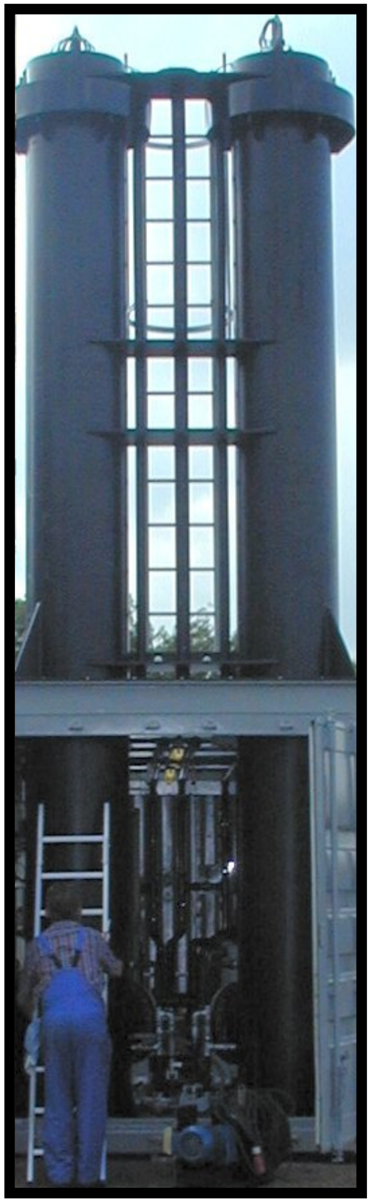




- **Denitification nitirifcation** and **phosphate** removal in separate tanks
- Complex designs and operations
- High recycle flows (energy consuming)
- Space consuming tanks to separate sludge and water
- Requires significant footprint
- Low biomass concentration



Why aerobic granular sludge?



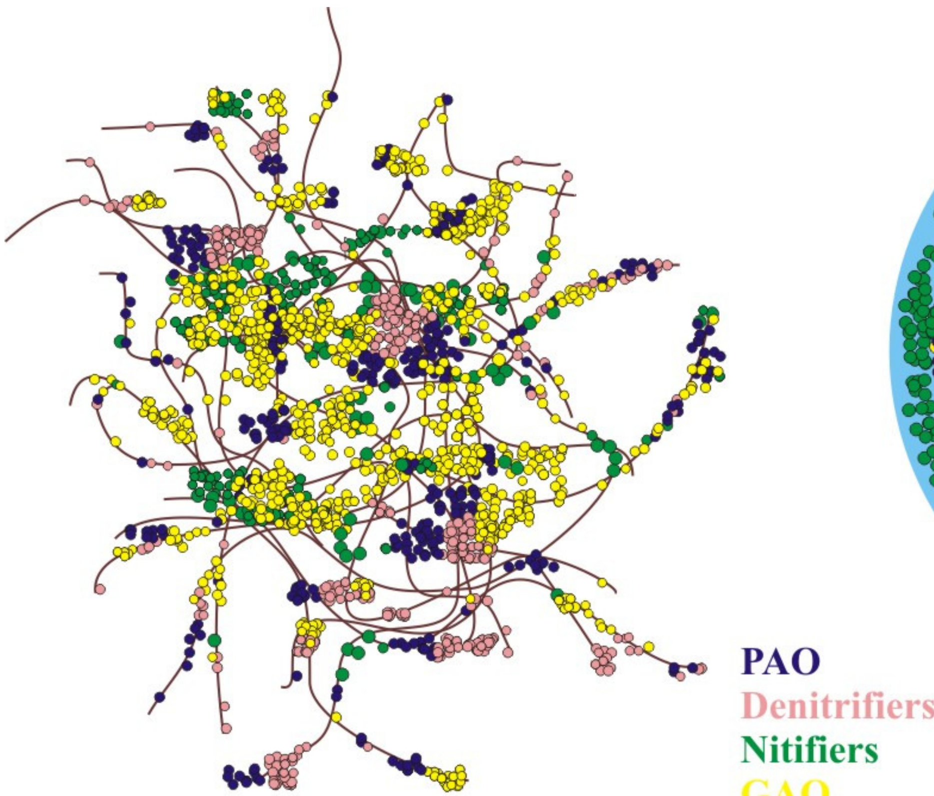
- Implemented New Technology
  - Laboratory Research world wide
  - Scaled-up: Africa, Netherlands, Portugal, etc.
  - Full-scale: Netherlands

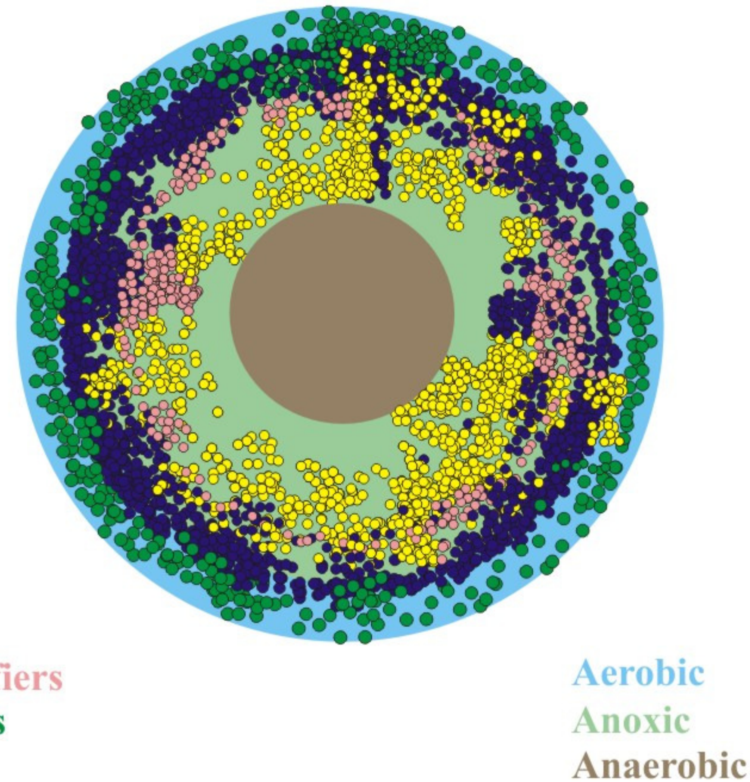
- Properties of Aerobic granular sludge
  - High settling properties due to compact structure
  - Selection for slow growing bacteria
  - Selection of bacteria due to segregation
  - High biomass concentration

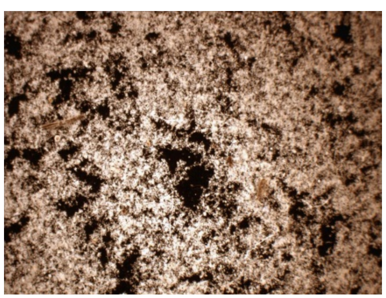
- Cost efficient
  - No extra settling tank
  - Simultaneous removal processes in one reactor
  - Simultaneous conversions in different layers in one granule
  - Reduction of space and energy requirements

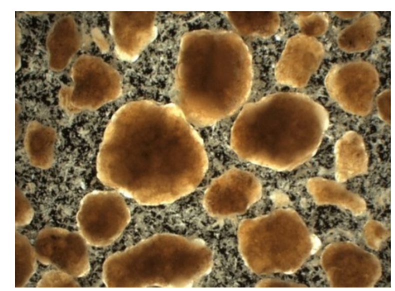
Granule versus flocs

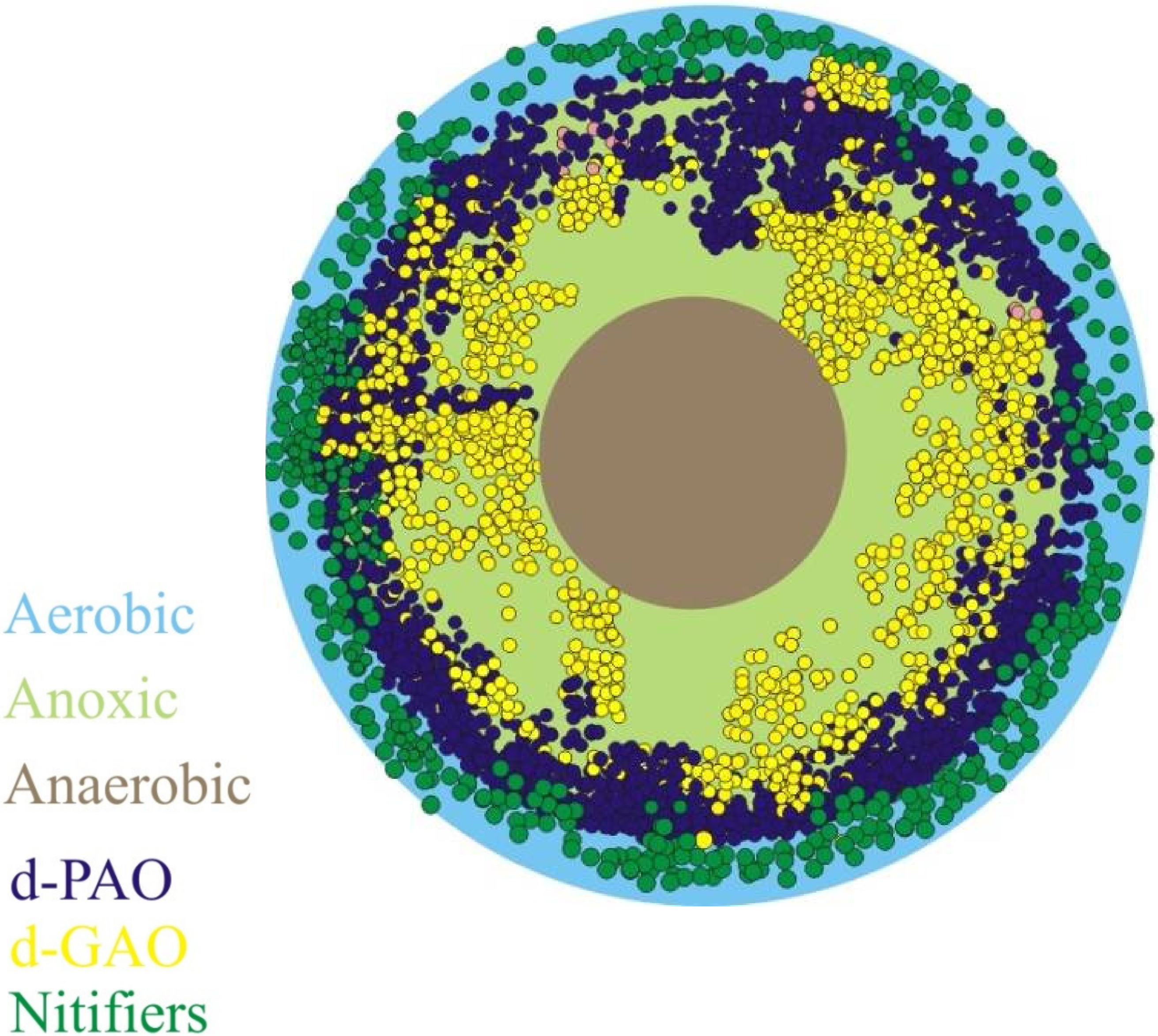
Flocs versus Granules



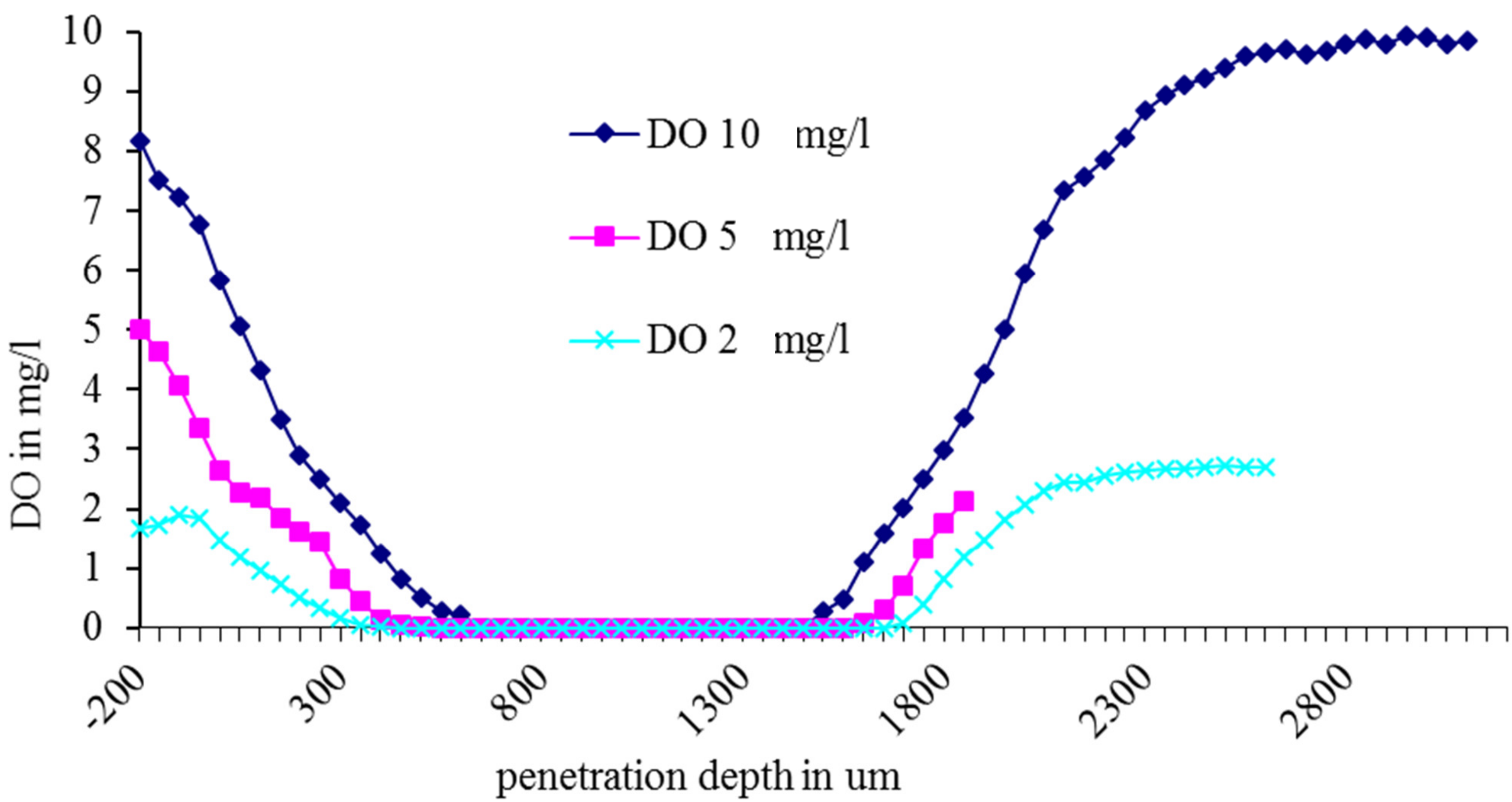




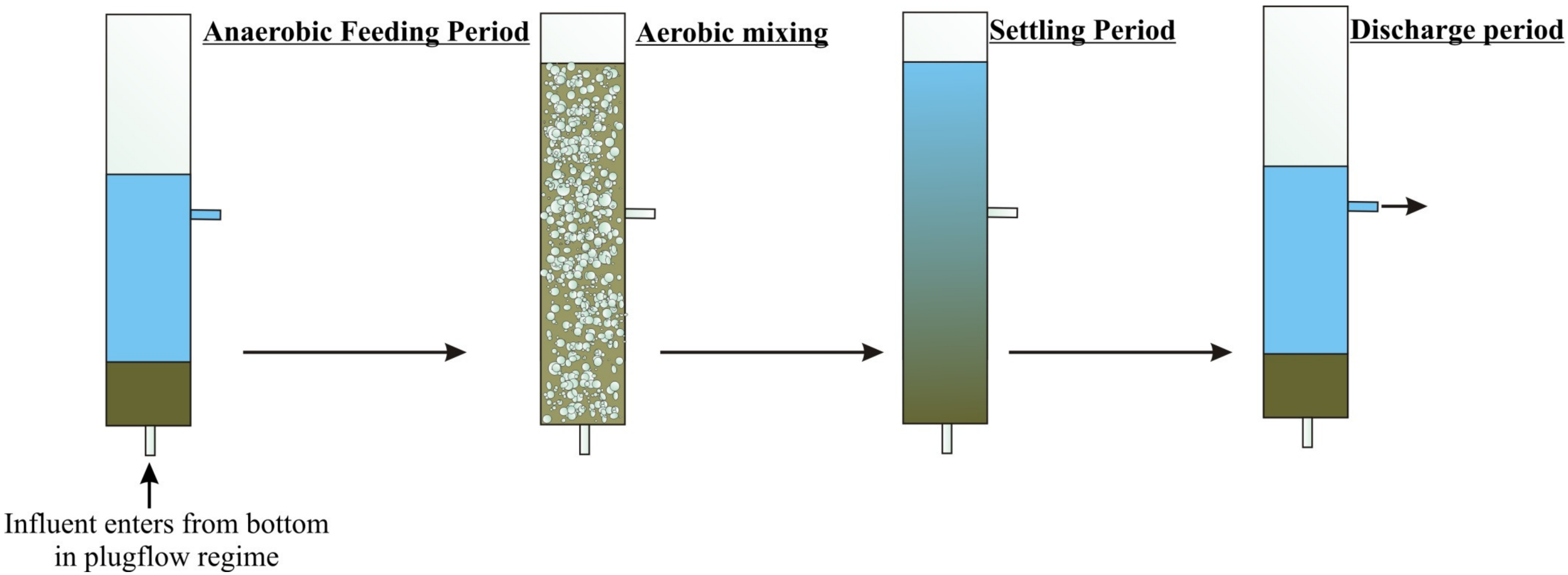



Aerobic
Anoxic
Anaerobic
d-PAO
d-GAO
Nitifiers

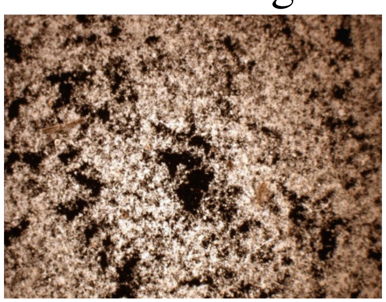
Substrate profile



Sequencing batch reactor



activated sludge

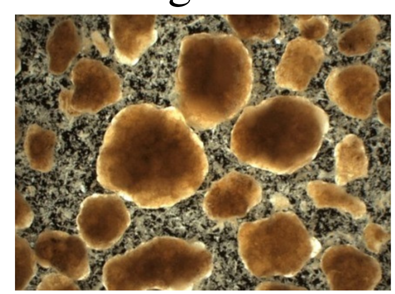


encourage change in biomass structure

Transformation

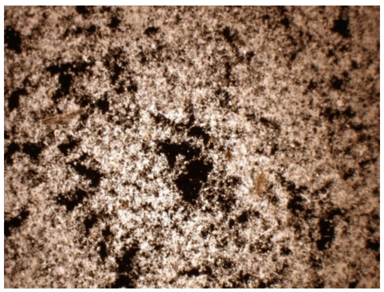
No carrier

aerobic granules



Granule selection criteria

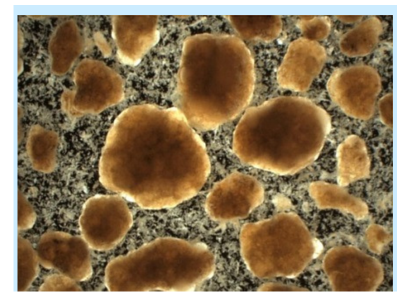
activated sludge



encourage change in biomass structure

transformation →

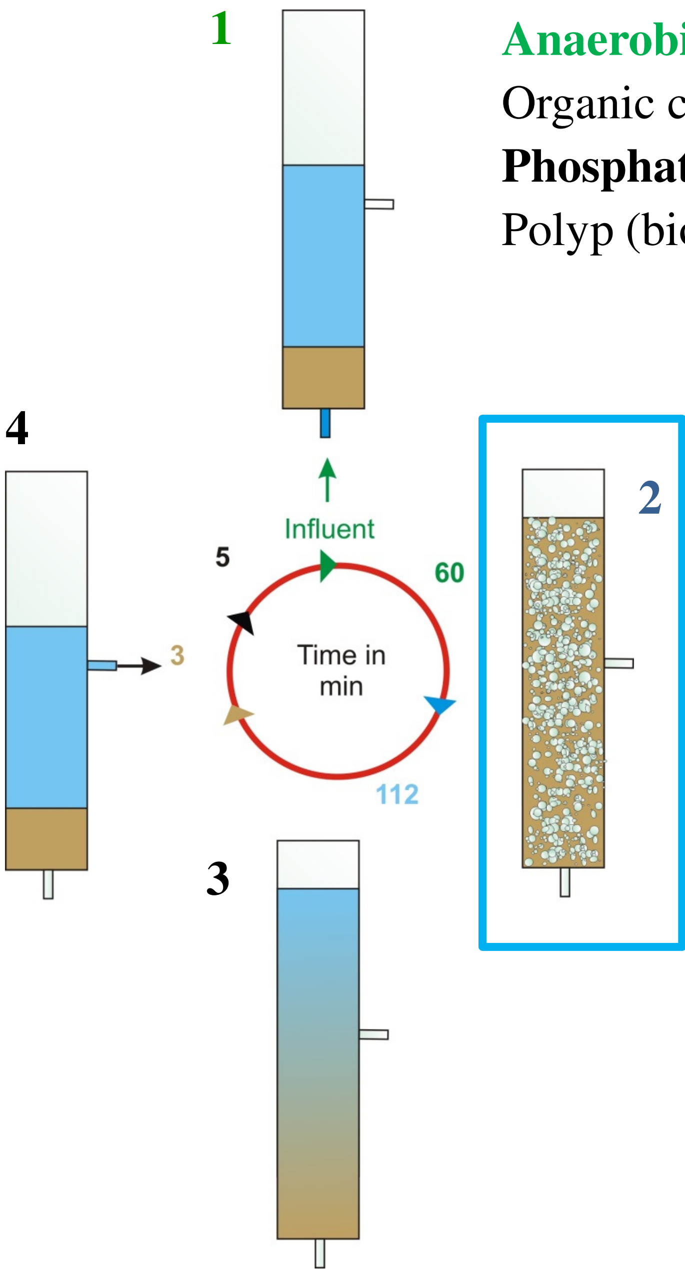
aerobic granules



Main selection principles

- Short settling time
- Anaerobic period promotes slow growers
  - P removal possible
- High shear
  - smooth granules
- Low DO-> more anoxic volume fraction
  - Good denitrification

Sequencing batch reactor



Anaerobic period

Organic carbon→PHB (biomass)

Phosphate release:

Polyp (biomass) → PO_4^{3-} (liquid phase)

Aerated reactor

Liquid phase: ammonium / phosphate

AOB:

$1NH_4^+ + 1.5O_2 \rightarrow 1NO_2^- + 2H^+ + 1H_2O$

NOB:

$1NO_2^- + 0.5O_2 \rightarrow 1NO_3^-$

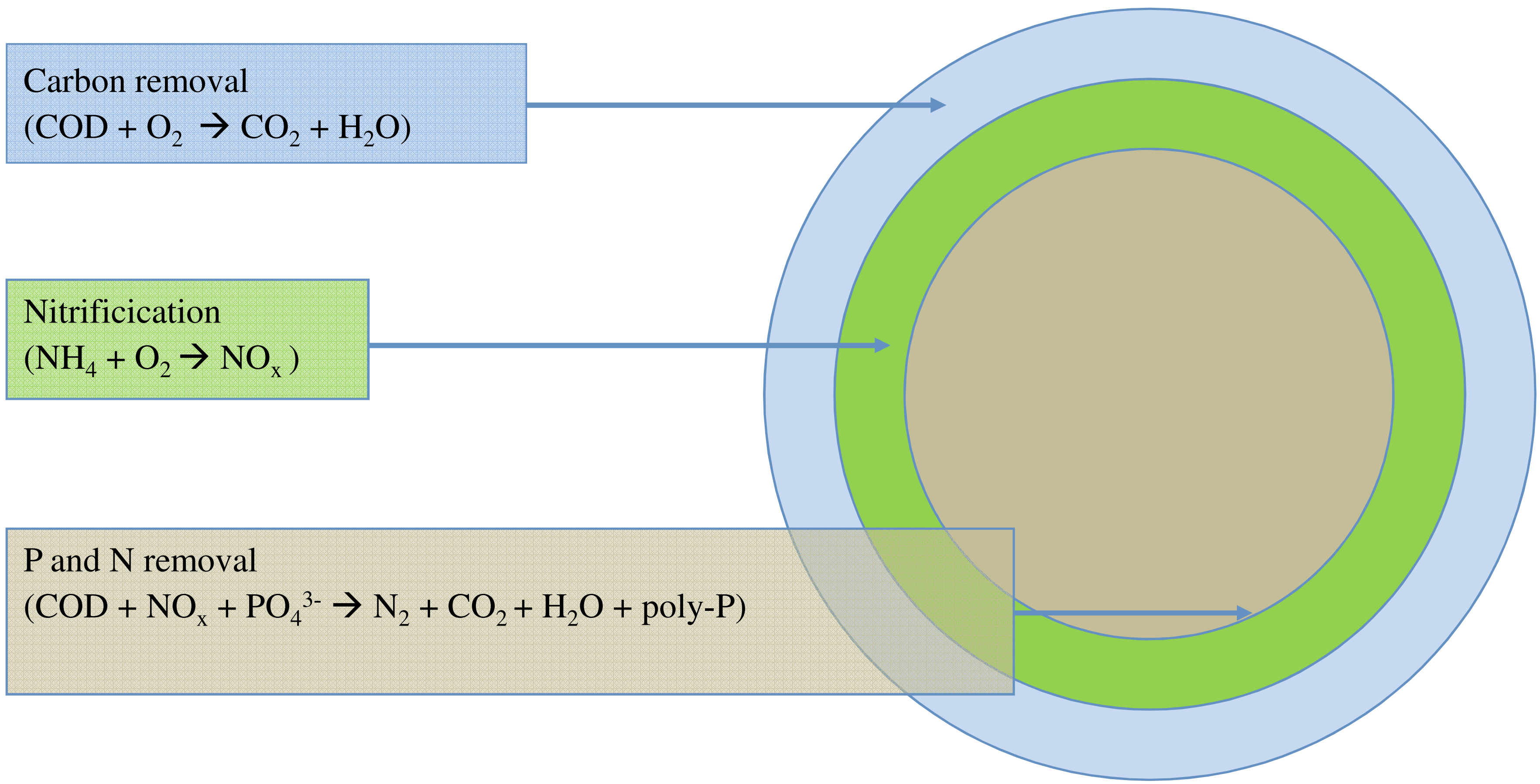
Di-nitrification:

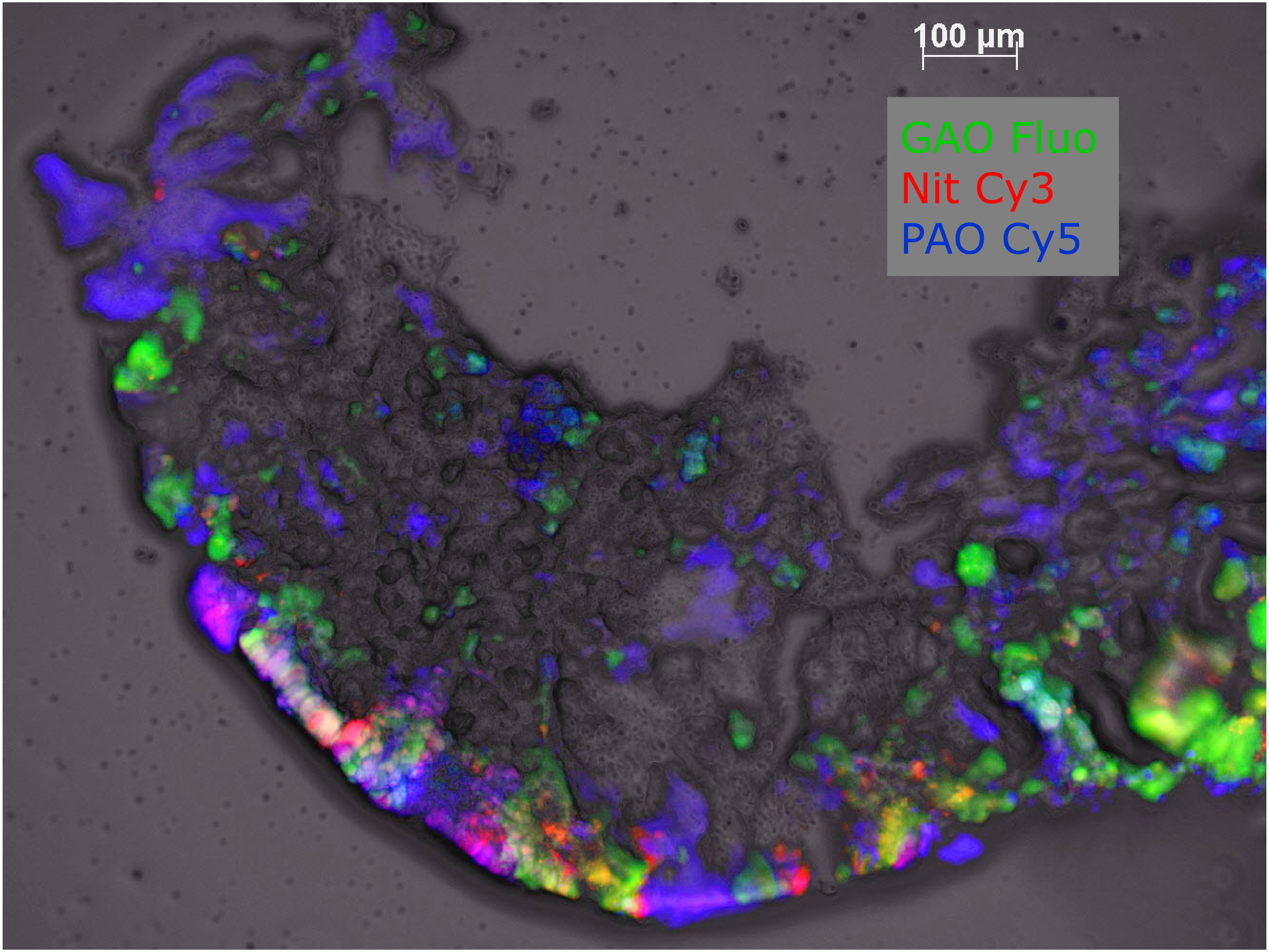
$NO_3^- + PHB \rightarrow N_2 + CO_2$

Phosphate removal:

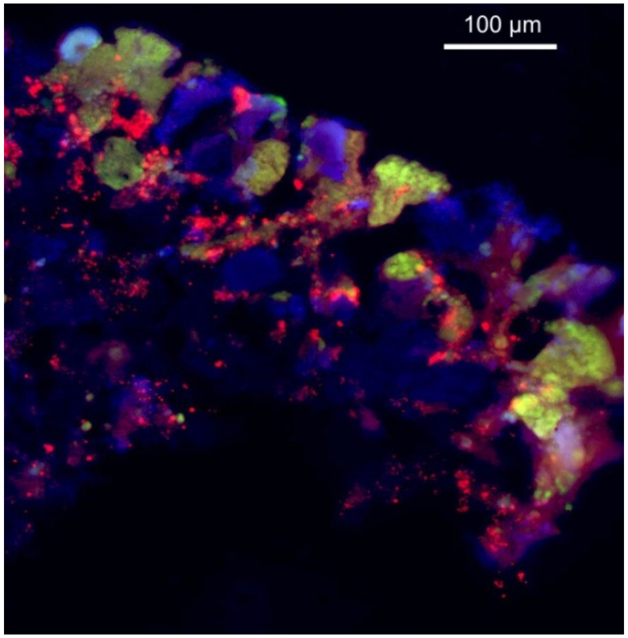
$PO_4^{3-} \rightarrow$ polyp (biomass)

Aerobic granular sludge

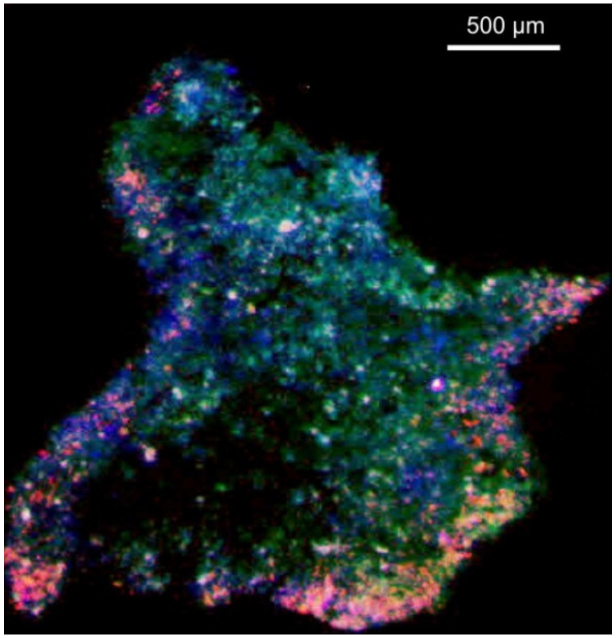



100 µm
GAO Fluo
Nit Cy3
PAO Cy5

FISH – bacterial distribution

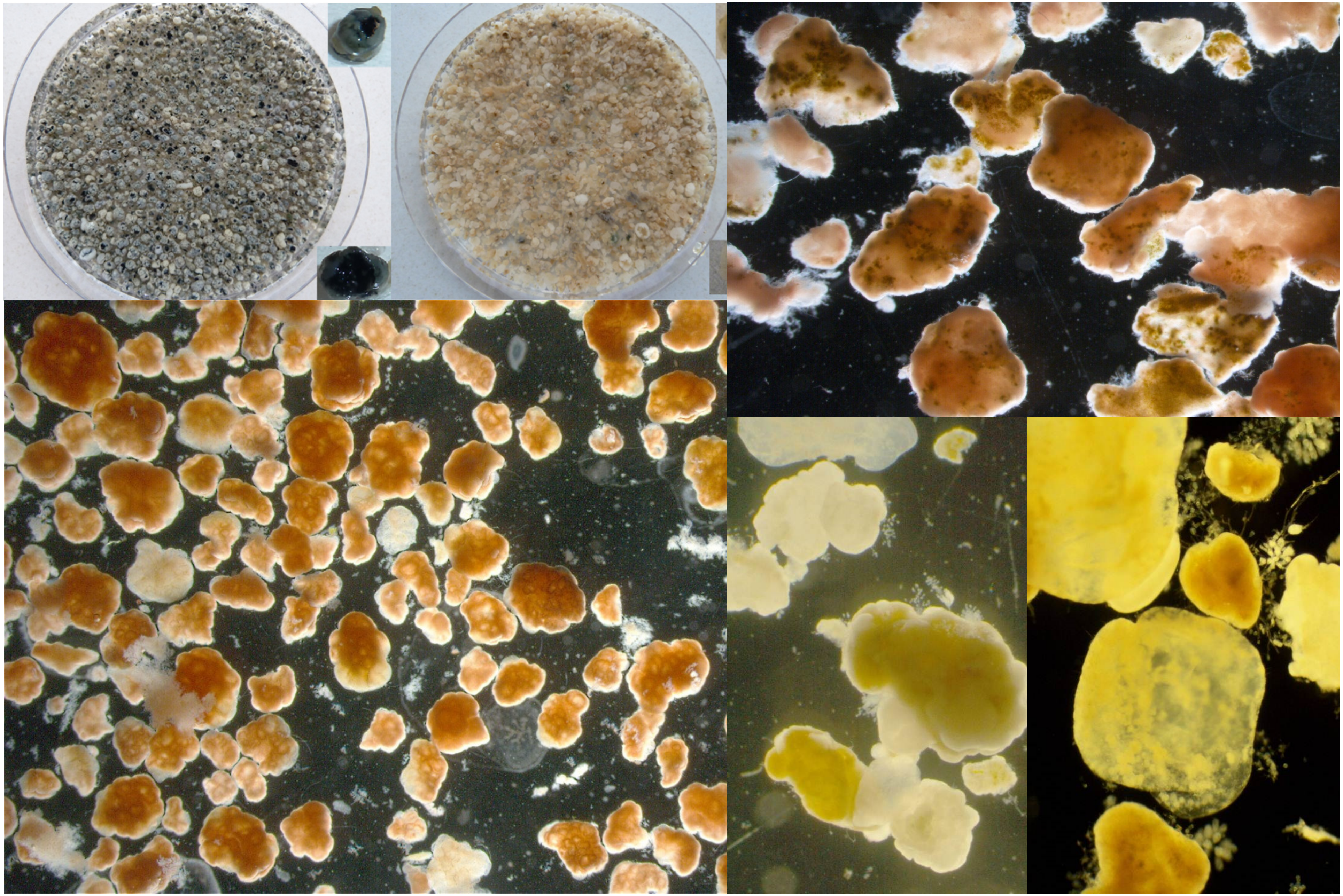


AOB NOB PAO

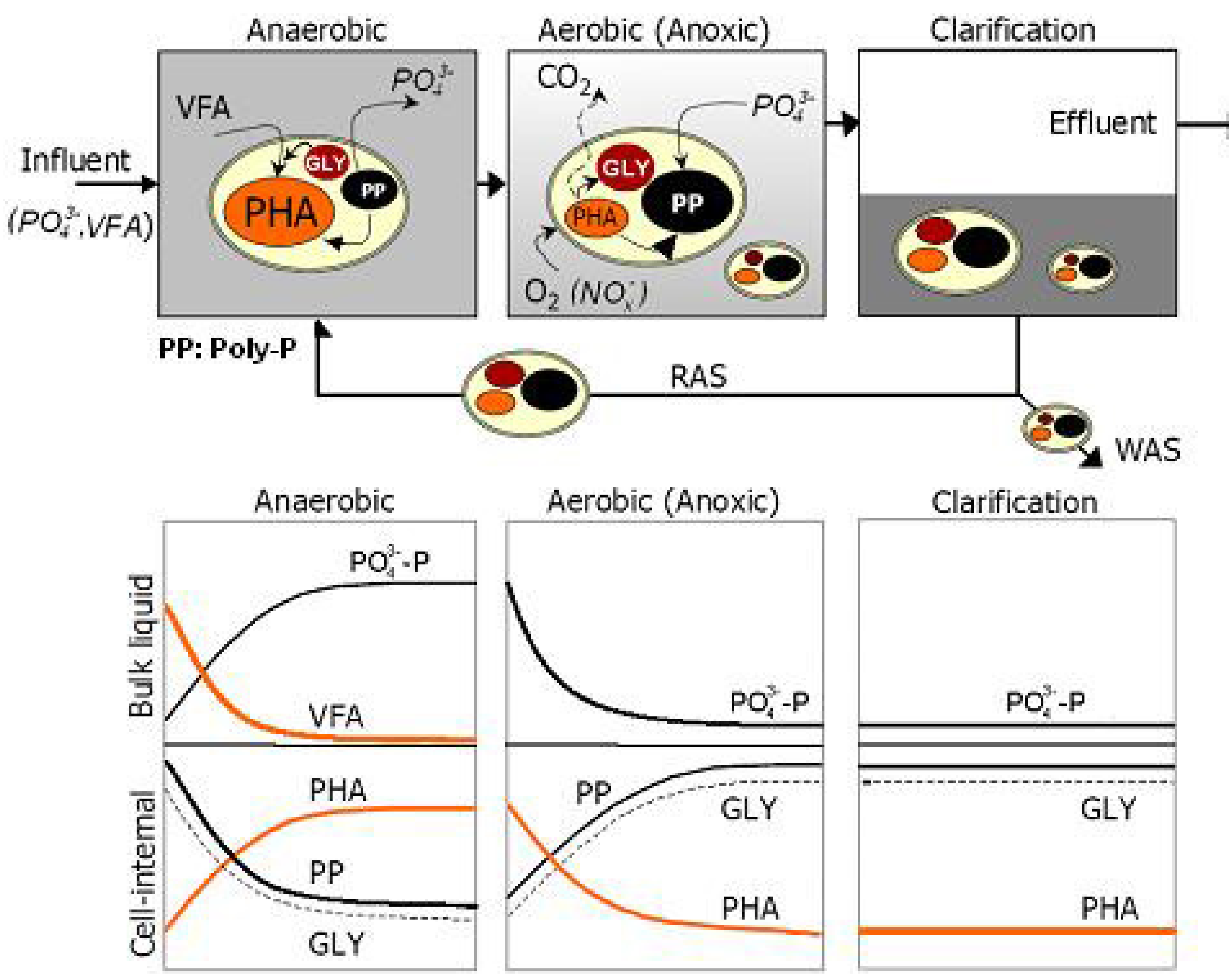


nitrifiers (AOB & NOB mix)
PAO GAO

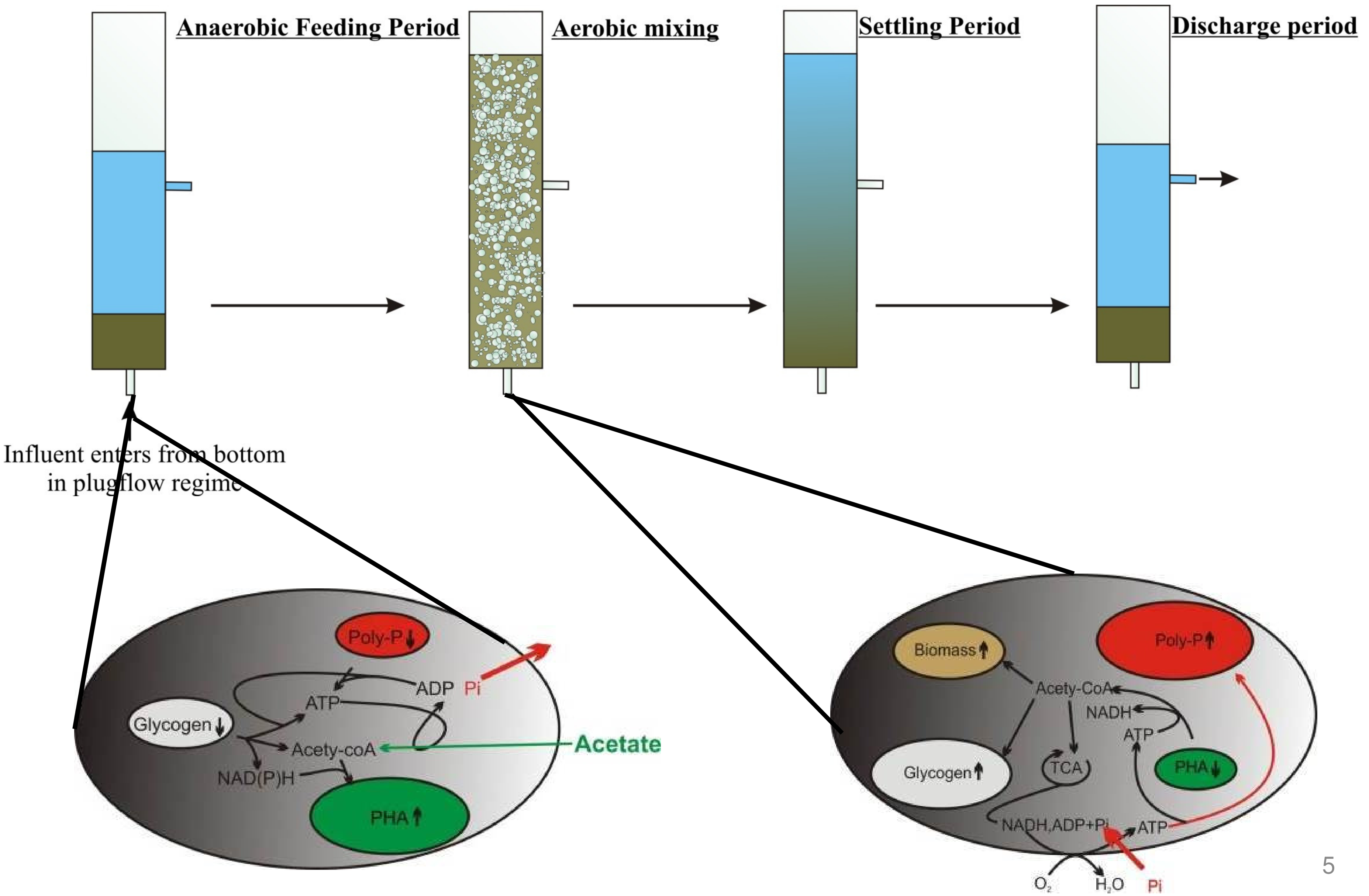
Granule images



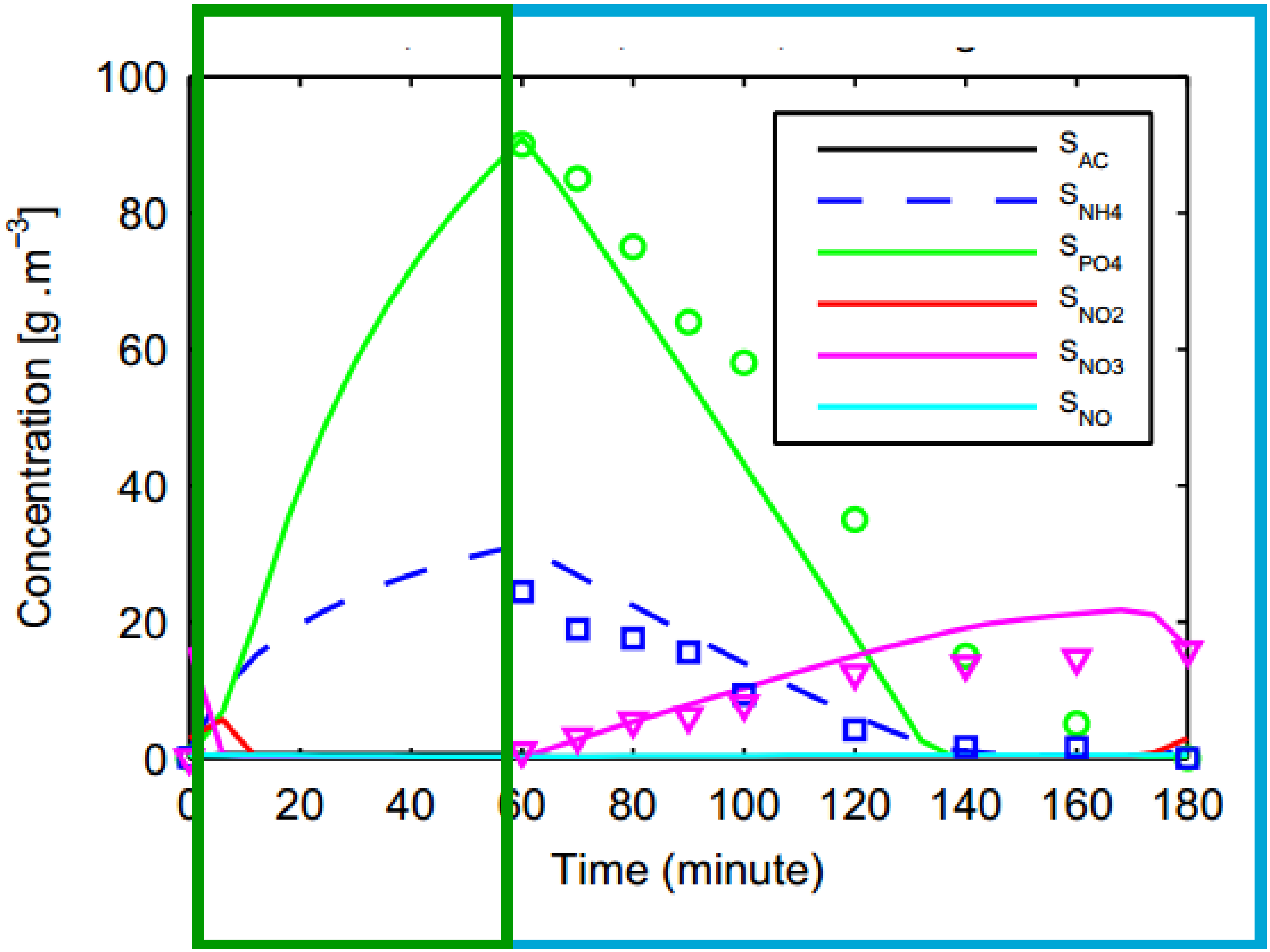
Zoom in P removal



Sequencing batch reactor



Biological Phosphate Removal



History

It all started with a beer at the October Fest and a friendly competition between two professors

Prof. Peter Wilderer
TU Munich

Prof. Mark van Loosdrecht
TU Delft

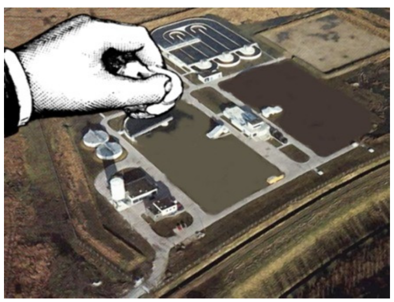
History

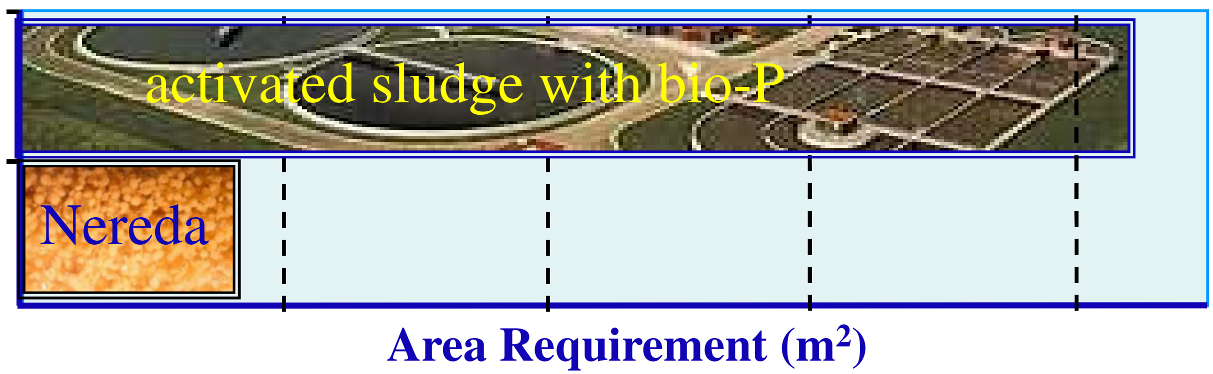
1993	Start labscale
1998	cooperation TUDelft / DHV
2003	1st pilot municipal wwt
2004	1st demo-installation industrial
2005	Nereda®
	1st industrial plant
2007	Nationaal Nereda Programma
2008	Demo- installations in SA en P
2011	1st full scale wwtp

Nereda reactors

- Granular sludge based
- 30 % Less Capital costs
- 25 % Energy Saving
- 70 % Less Space

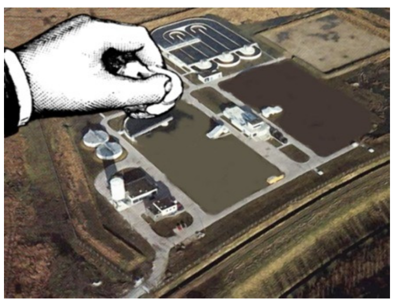
Key advantages Nereda

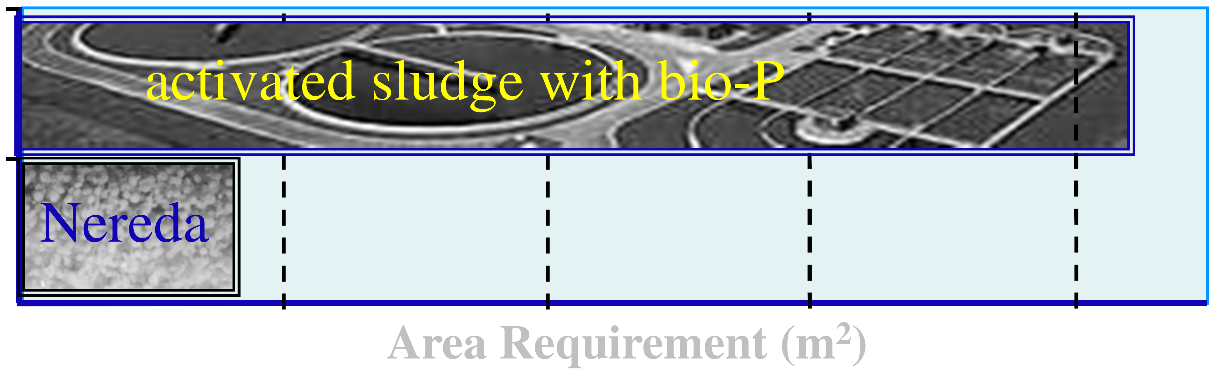




- 75% smaller footprint:
  - high biomass concentration
  - no selectors, no anaerobic tanks, no clarifiers

Key advantages Nereda

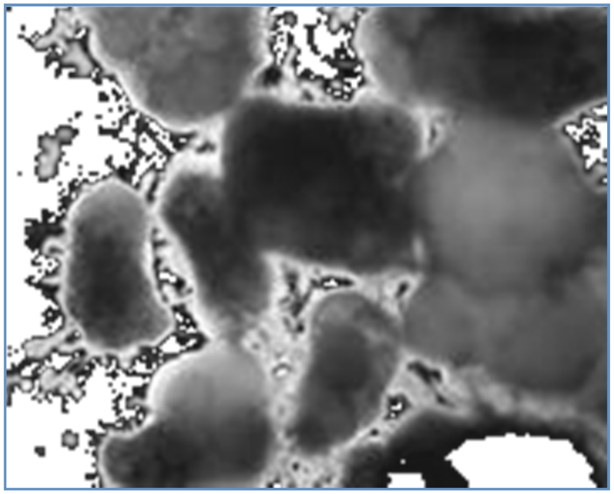


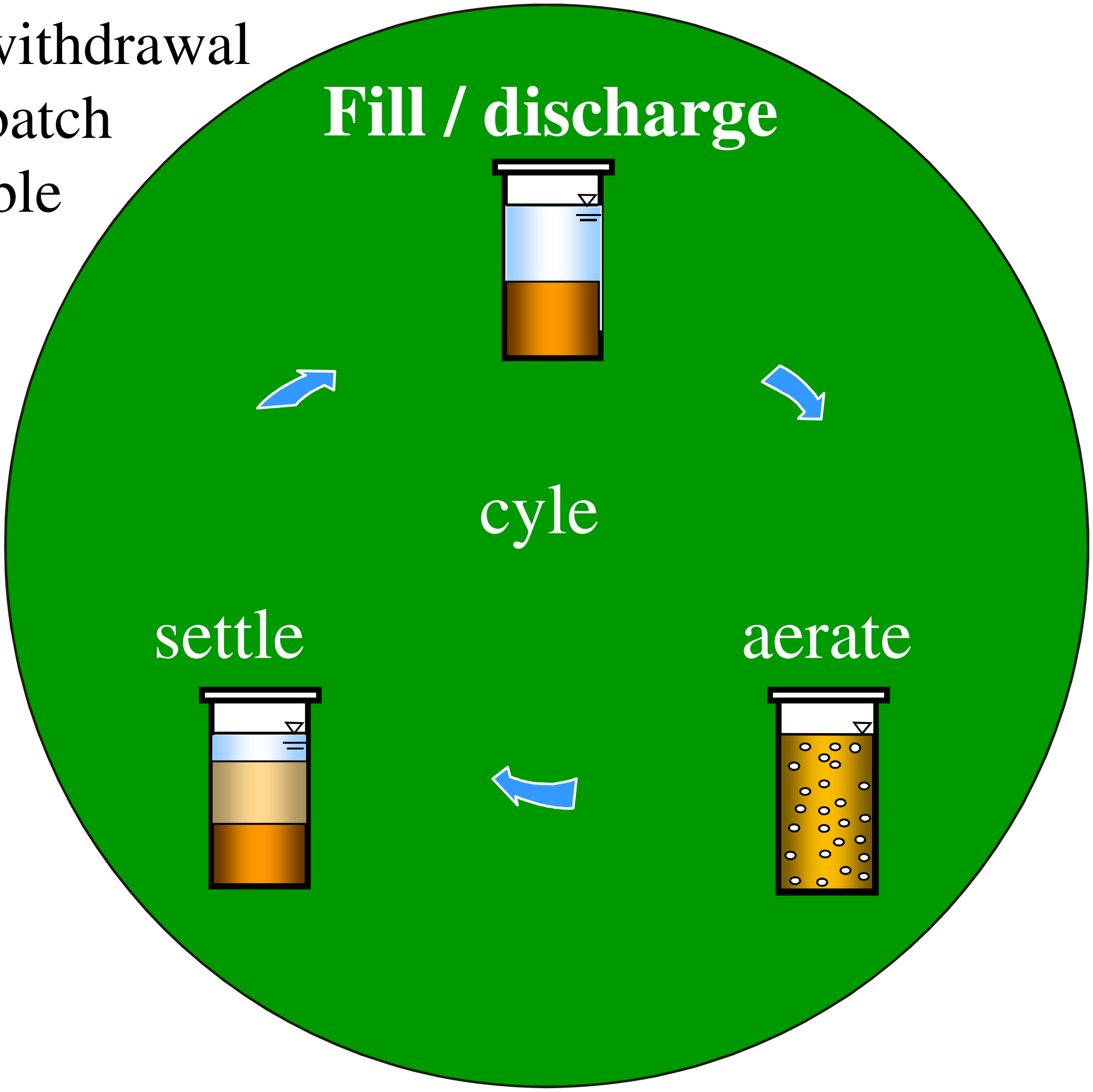


- >25-35% energy savings:
  - less rotary equipment
  - efficient aeration
- lower construction & operation costs

Process cycle –full scale: combined fill/drain

- Simultaneous fill and withdrawal
- 3 reactors operated in batch
- Continuous flow possible
- No buffer tank





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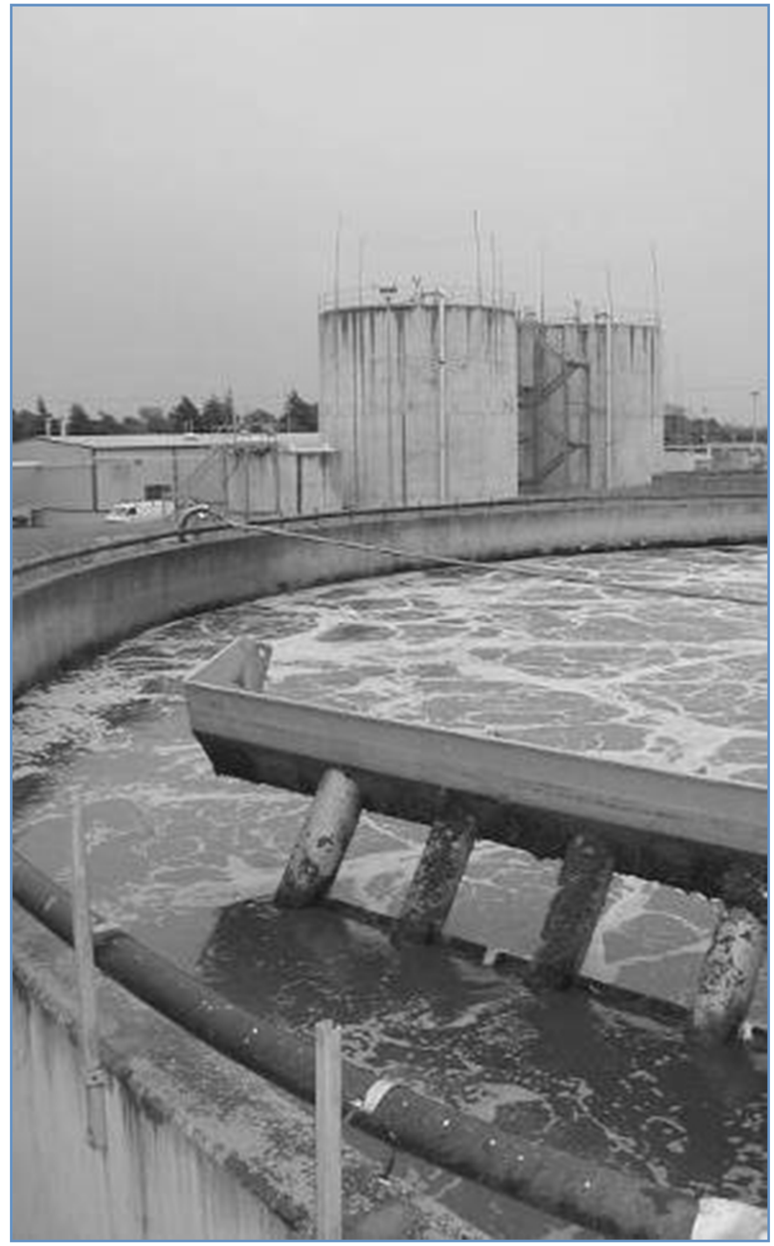


Pilot plant Epe in the winter <10 °C

- 70-90% granules / 6 -12 kg/m^3
- Settling: SVI_5 = 30 – 90 ml/g
- Typical effluent quality
  - SS 10 – 20 mg/l
  - NH_4 en NO_x < 5 – 10 mg/l
  - P_{ortho} 0,1 – 2 mg/l (without chemicals)

Comparison

parameter	 BNR Activated Sludge	Nereda® The natural way of treating wastewater
effluent quality	good	similar or better
process stability	good	similar or better
footprint	100%	25%
energy consumption	100%	< 65-75%
sludge production	100%	similar or lower
MLSS in reactor	3-5 kg/m3	10-15 kg/m3
CAPEX	100%	significantly lower
OPEX	100%	significantly lower

Demo- installation South Africa

Parameter (oktober 2009)				
	Influent mg/l	Effluent mg/l	Limits mg/l	Removal %
COD	2.470	87 (x)	75	96,5%
NH_4-N	60	0,4	6	99,3%
NOx-N		8,2	15	
NH_4-N + NO_x-N	60	8,6	20	85,7%
Ortho-P	10	0,2	10	97,4%
Suspended Solids	1.117	7	25	99,4%

Enduser advantages - summary

Cost-effective

- Less mechanical equipment
- No separate clarifiers /small footprint
- Low Operation & Maintenance costs
- No/minimal chemicals and related waste
- Lower energy consumption

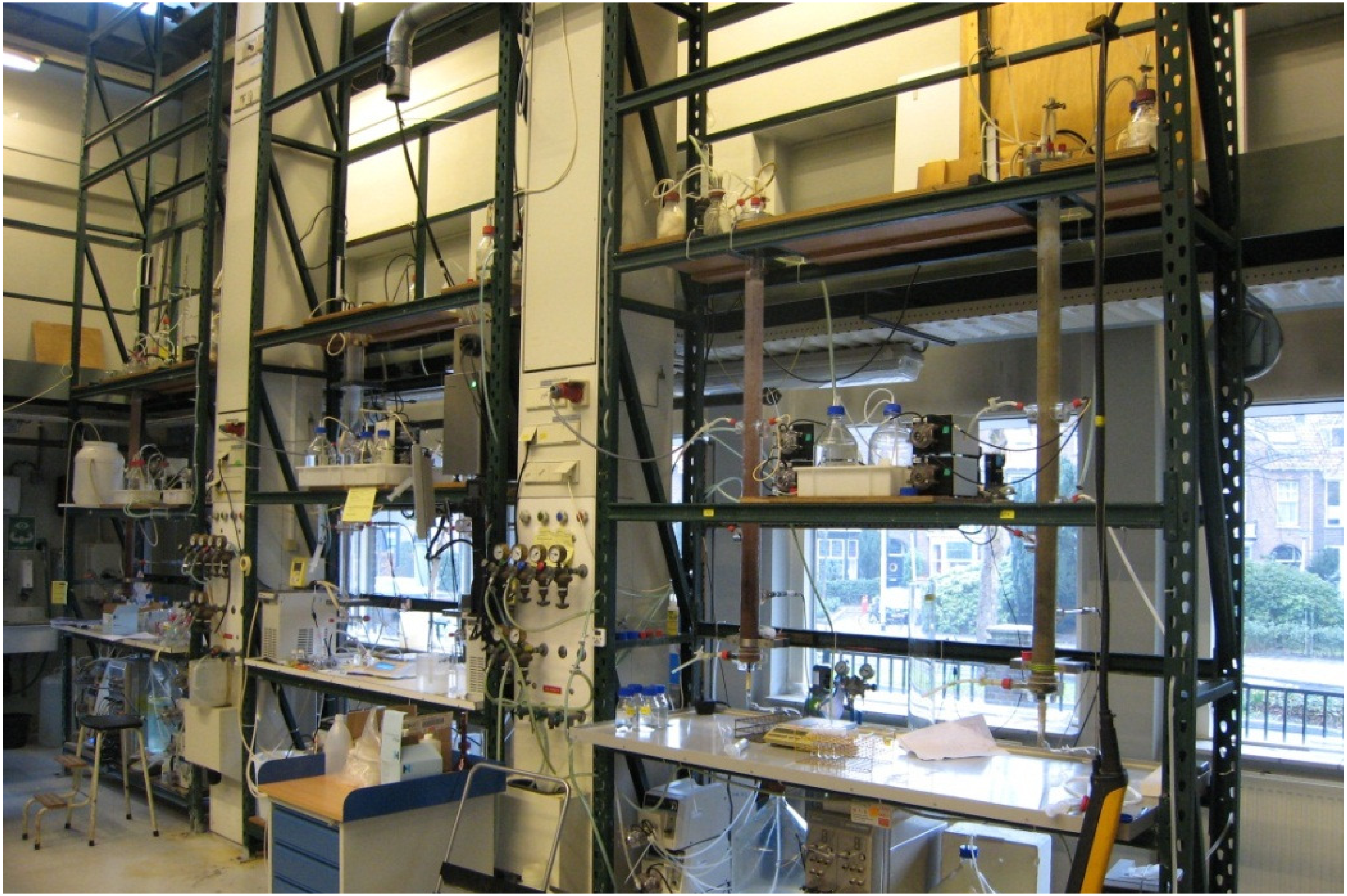
Sustainable

- Remarkably high effluent purity
- No/minimal waste generating chemicals
- bio P removal
- Significantly lower energy consumption
- Less construction materials required
- A factor four smaller footprint

Biomass Advantages:

- Excellent settling properties
- High biomass concentration
- Simultaneous biological N- and P-removal
- Simple one-tank concept (no clarifiers)
- Pure biomass, no support media required

Lab reactors



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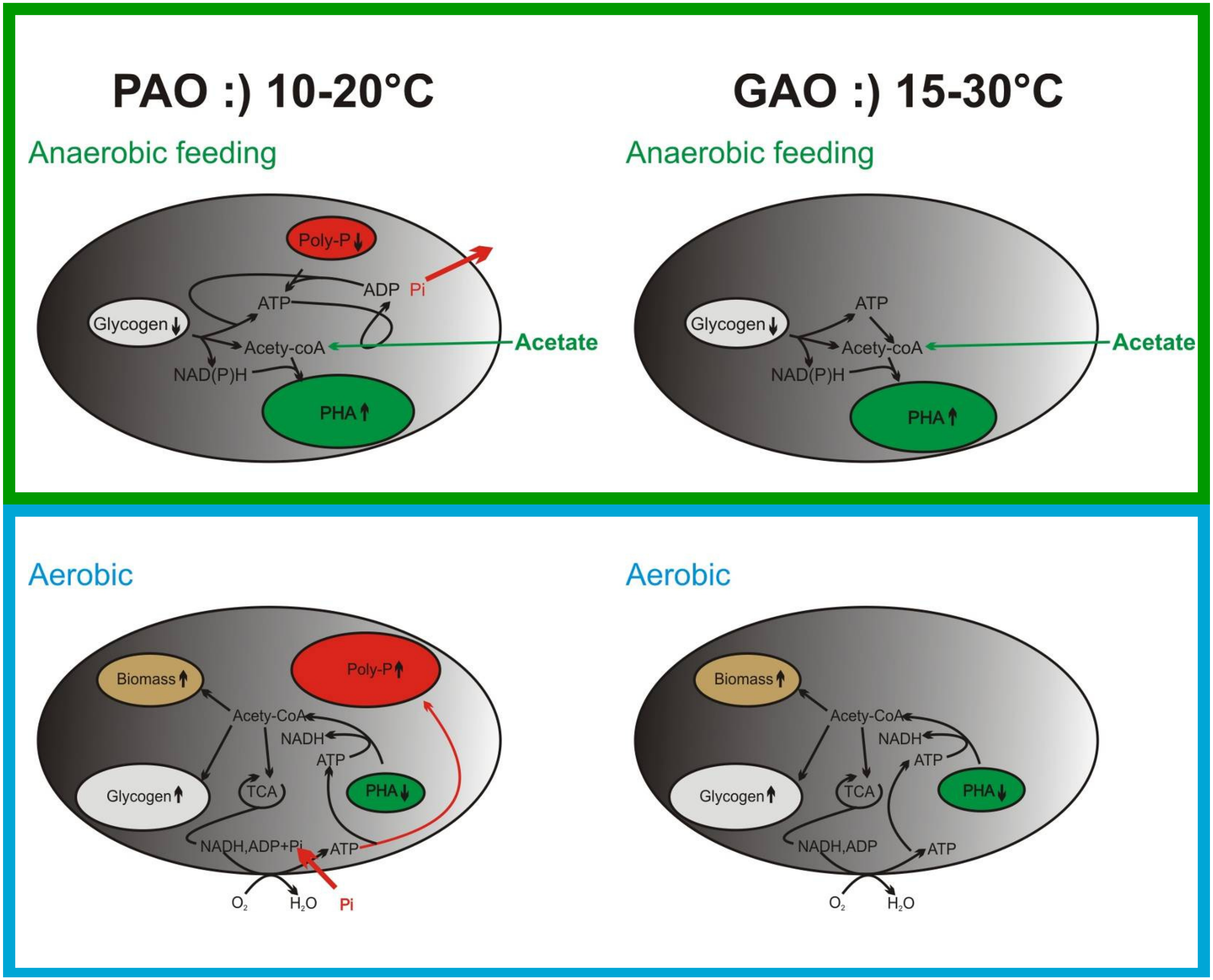
UNIVERSITY *of* WASHINGTON

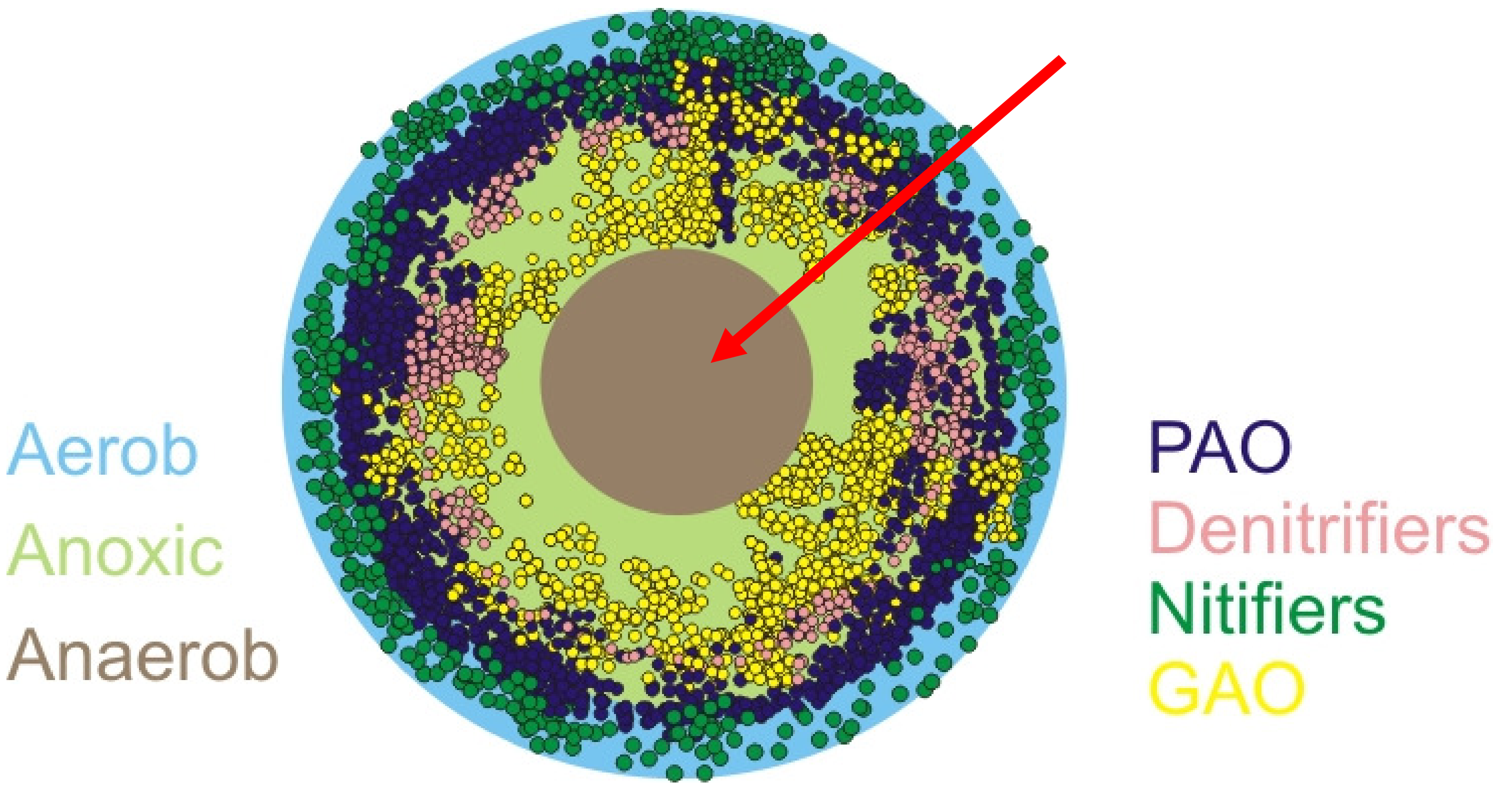
Biological Phosphate Removal



Competition PAO and GAO

Temperature	100 % HAc			75-25 % HAc-HPr			50-50 % HAc-HPr			100 % HPr		
pH	6.0	7.0	7.5	6.0	7.0	7.5	6.0	7.0	7.5	6.0	7.0	7.5
30 °C	*Competi*	*Competi*	*Competi* *PAO*	*PAO* *Alpha*	*PAO*	*PAO*	*Alpha*	*Alpha* *PAO*	*PAO*	*Alpha*	*Alpha*	*Alpha*
20 °C	*Competi* *PAO*	*Competi* *PAO*	*PAO*	*PAO*	*PAO*	*PAO*	*PAO*	*PAO*	*PAO*	*Alpha*	*Alpha* *PAO*	*PAO*
10 °C	*PAO*	*PAO*	*PAO*	*PAO*	*PAO*	*PAO*	*PAO*	*PAO*	*PAO*	*PAO*	*PAO*	*PAO*

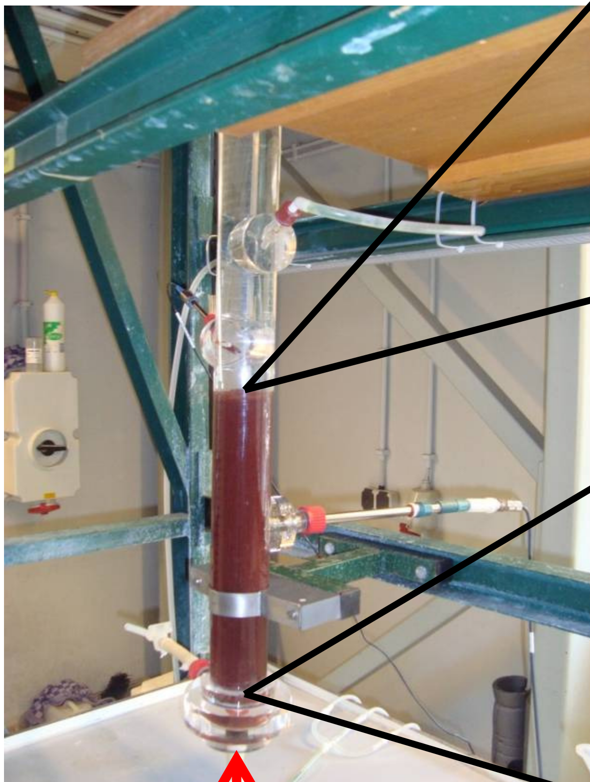
Segregation inside granule

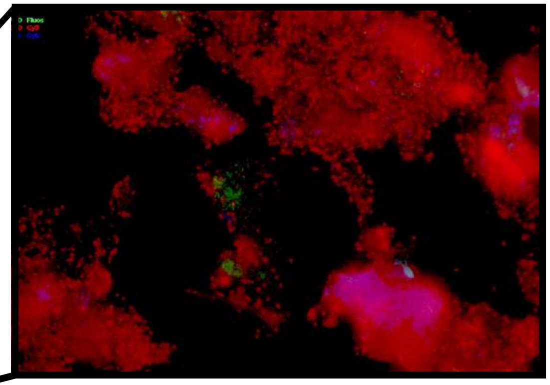


Segregation inside reactor

Reactor

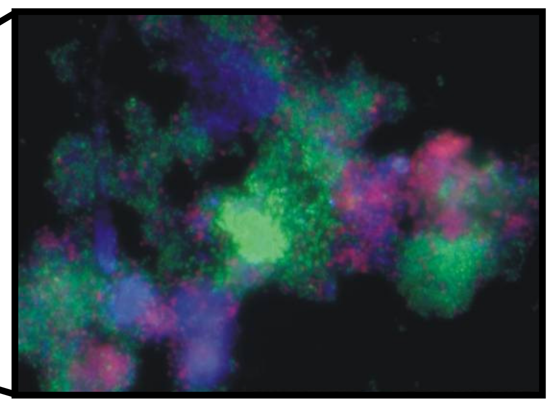
P-removal ~50%





Density [g/l]	**1004±3.8**
Diameter [mm]	**0.8±0.08**
Ash [%]	15±4

PAO, GAO



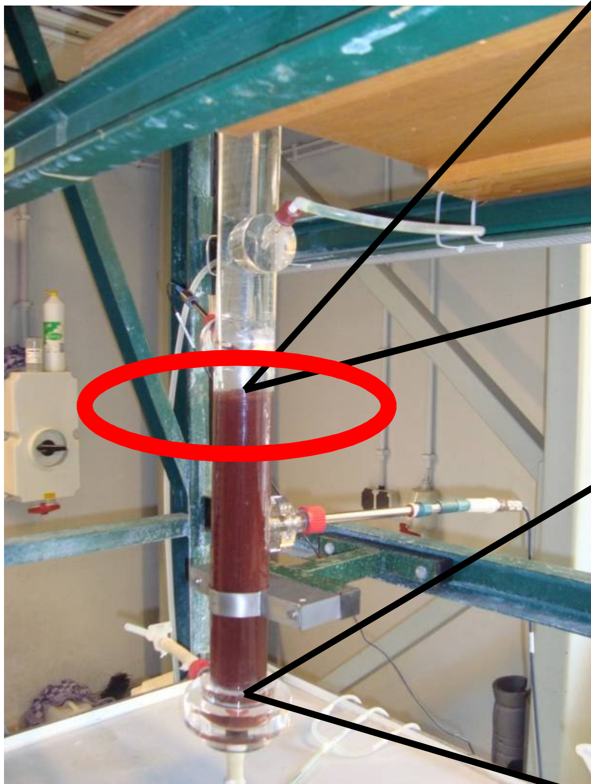
Density [g/l]	**1018±12.8**
Diameter [mm]	**1.1±0.15**
Ash [%]	34±5

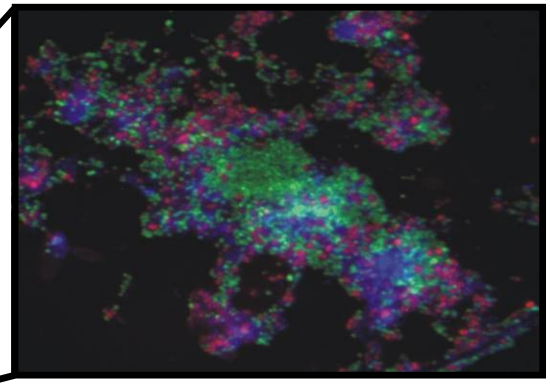
substrate

First come first serve: who ever is in the bottom gets more substrate and can grow bigger in size

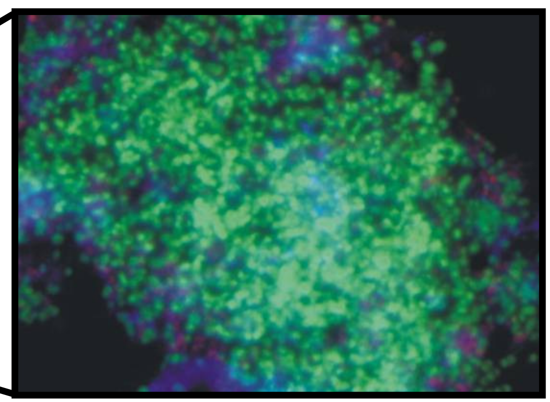
Selective removal <u>top</u>

P-removal ~**95%**





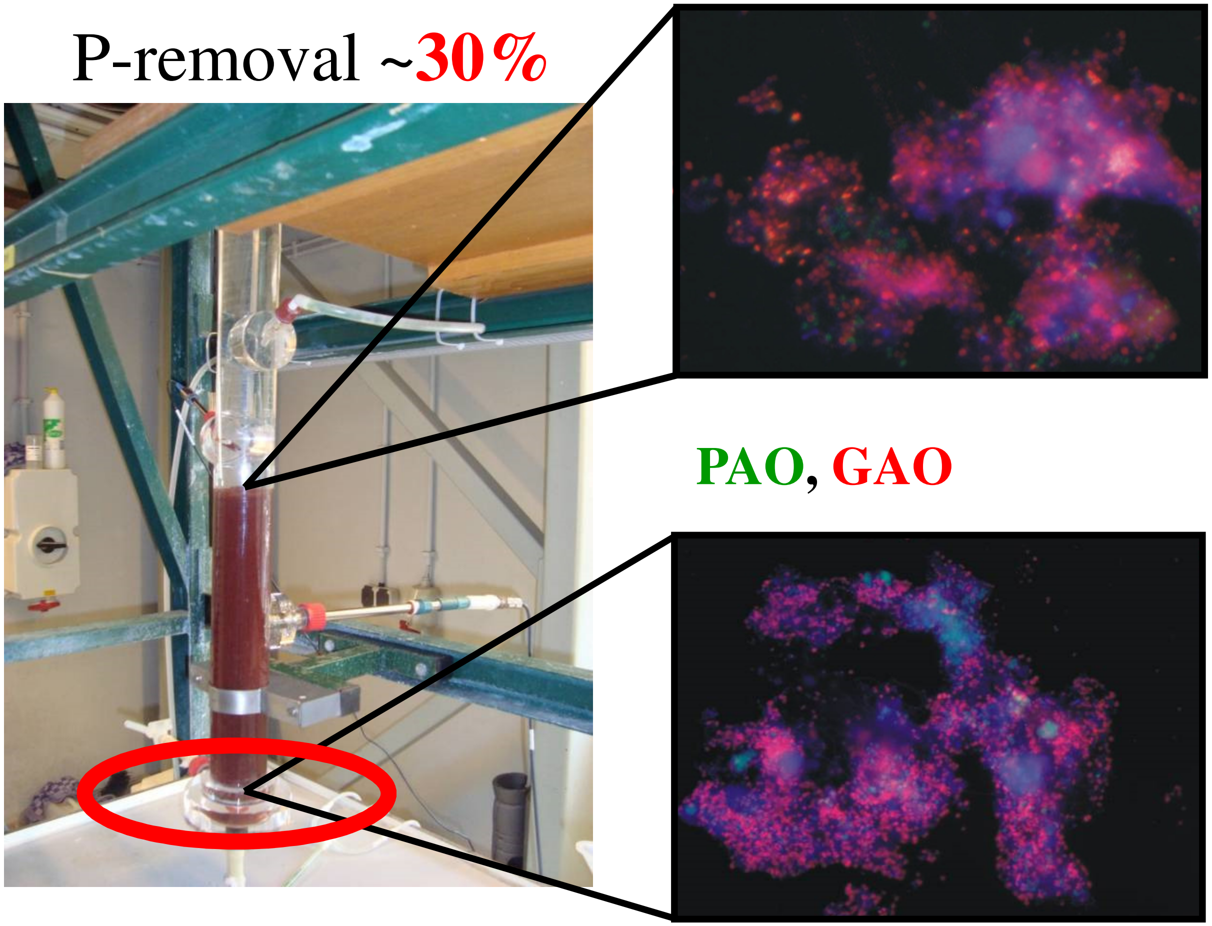
PAO, **GAO**



Sludge removal from the <u>top</u> of the sludge <u>favoured **PAO**</u> over **GAO**

Selective removal <u>bottom</u>

P-removal ~**30%**

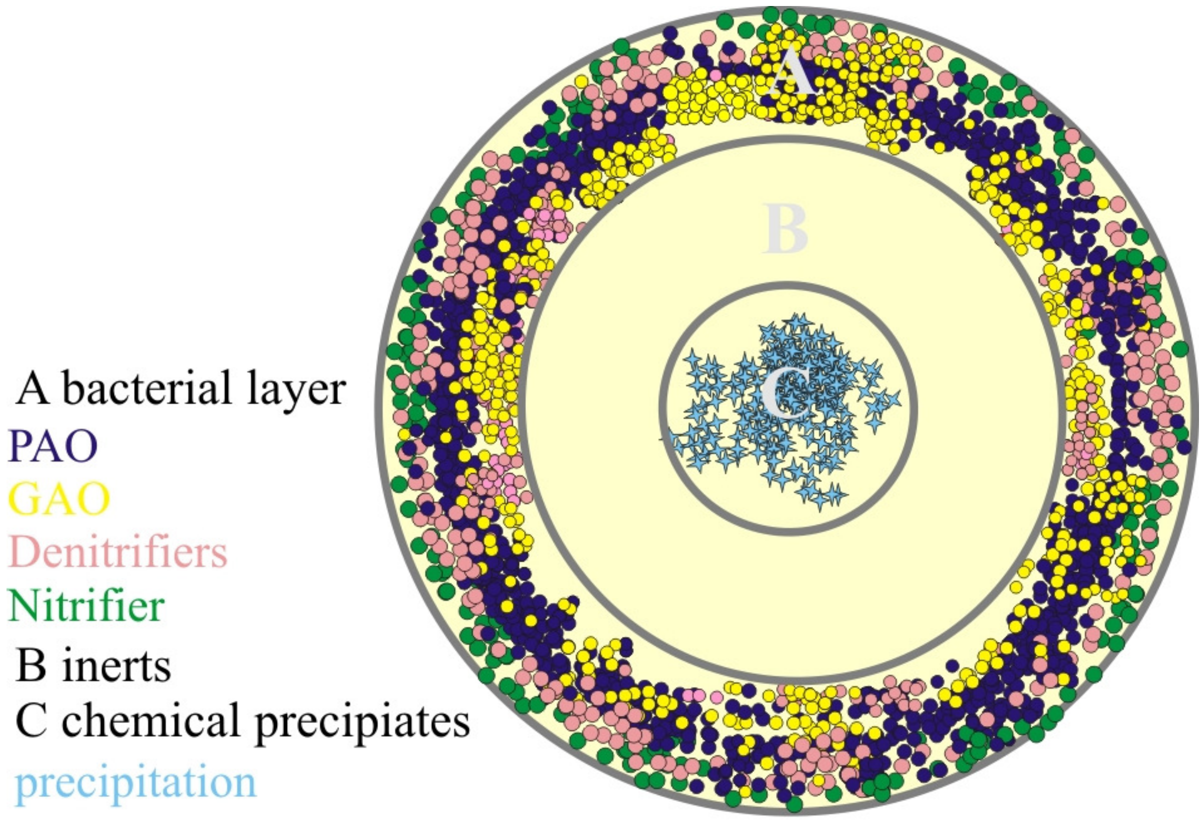


- Sludge removal from the <u>bottom</u> of the sludge <u>favoured **GAO**</u> over **PAO**

Physical properties

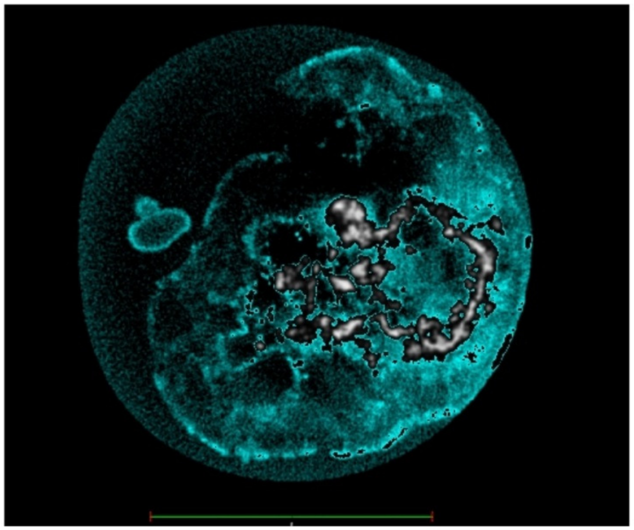
Physical properties of bottom and top granules		
Parameter	**Top (GAO)**	**Bottom (PAO)**
Density [g/l]	1004±3.8	1018±12.8
Average diameter [mm]	0.8±0.08	1.1±0.15
Ash content [%]	15±0.11	34±0.14
Settling velocity Calculated [m/h]	20±4.7	80±9.3
Settling velocity Measured [m/h]	n.m	66±8.6

What contributes to density?

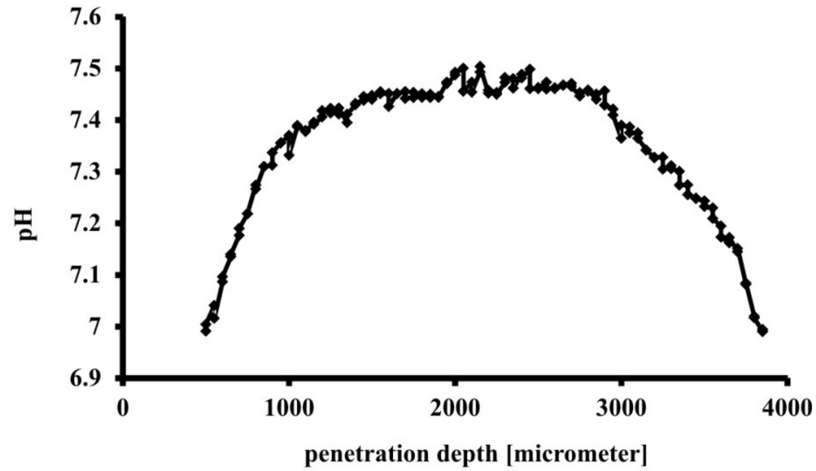


What contributes to density?

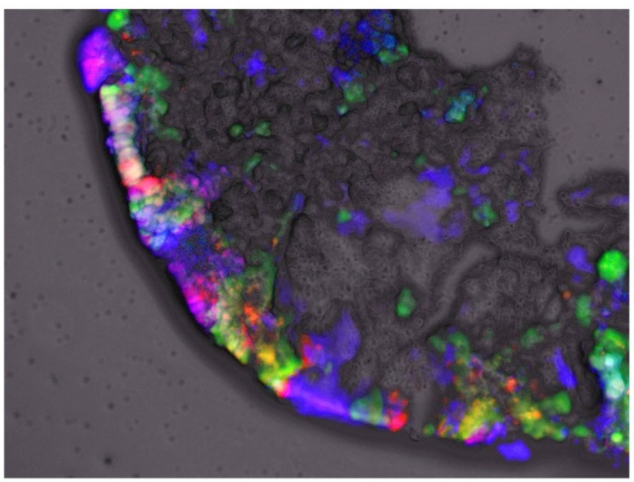
A) CT scan



B) pH microelectrode



C) sliced granule

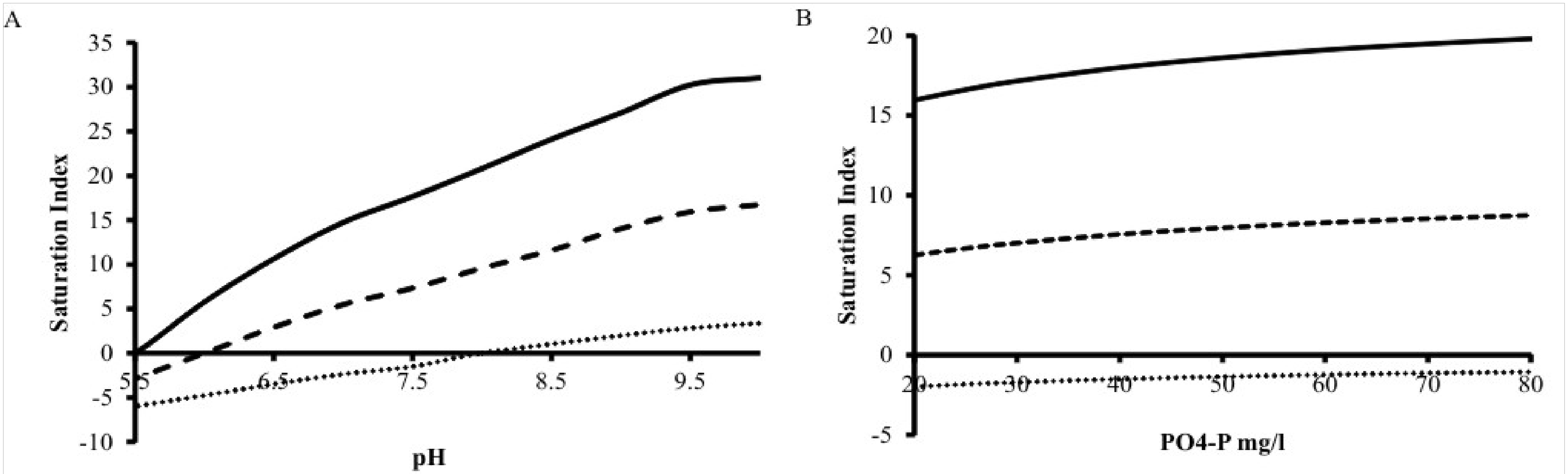


Slide 40

M1 In the anabolic pathway of anaerobic ammonium oxidation carbonate is reduced and assimilated into biomass. This is a proton consuming process which causes an increase of the pHin the bulk.

The uptake of the acidic compound acidic acid by PAOs and GAOS leads to a pH increase (removal of H+ ions from the bulk).
Mari, 12/9/2012

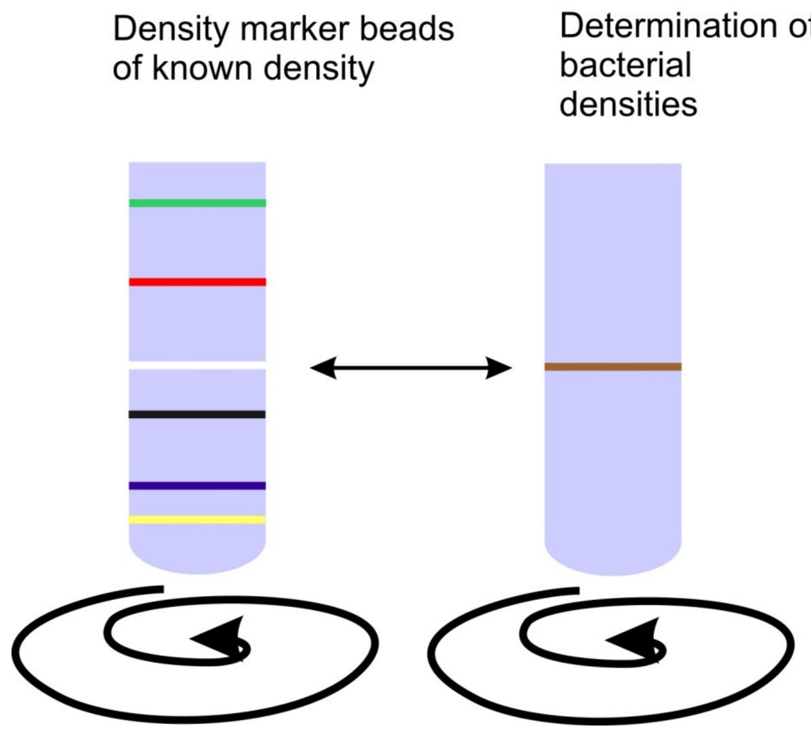
Microbial induced precipitation



Influence of A) pH and B) phosphate concentration (pH 7) on precipitation equilibria of Fluoroapatite (straight line), Hydroxydicalciumphosphate (dashed line) and Hydroxyl-apatite (dotted line) at 20°C

Percoll density centrifugation

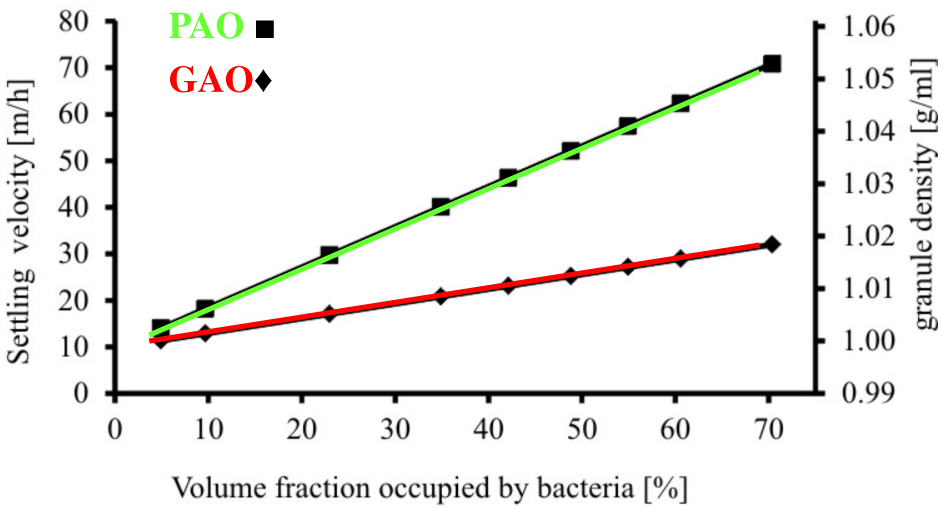
Bacterium	Density [g/ml]
PAO	1.0765±0.084
GAO	1.031±0.055



Winkler M-K.H., Kleerebezem R., M. Strous, Chandran K, and van Loosdrecht M.C.M., 2012, Factors influencing granular density *Applied environmental biotechnology*

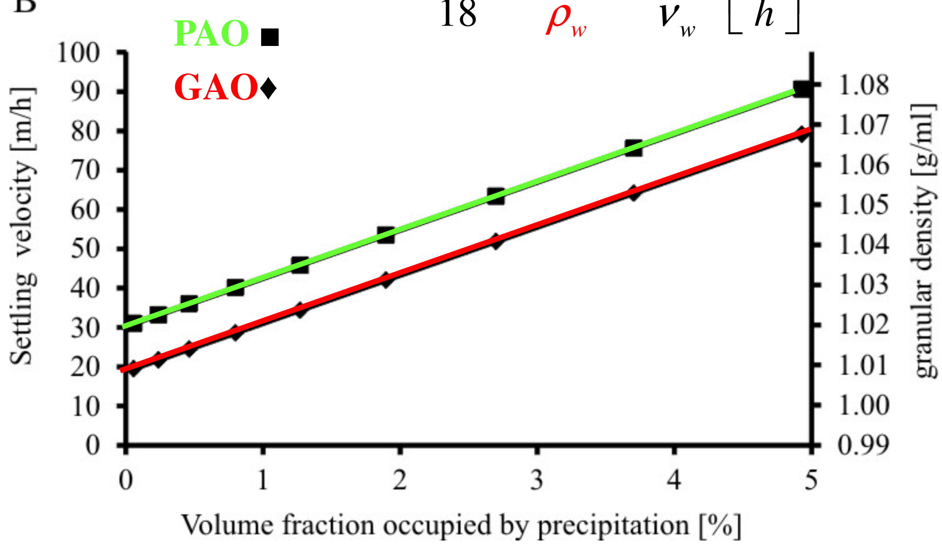
PAO- GAO and precipitates

A



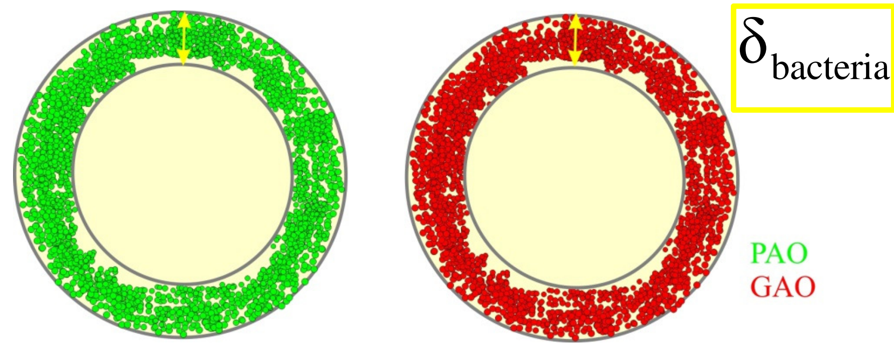
$$SV = \frac{g}{18} \cdot \frac{\rho_p - \rho_w}{\rho_w} \cdot \frac{d_p^2}{\nu_w} \left[\frac{m}{h}\right]$$

B



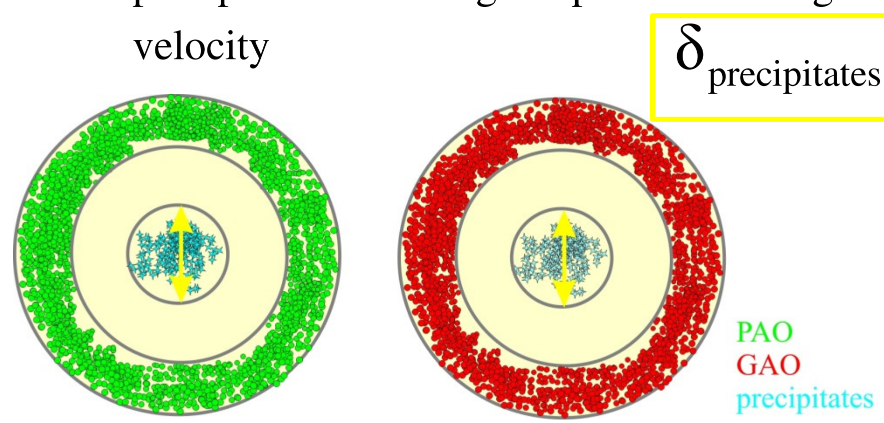
Change in volume fraction of bacteria at <u>constant diameter</u>:

- Density of bacteria changes settling velocity



Change in volume fraction of precipitates at <u>constant diameter</u>:

- Small changes in volume fraction of precipitates have large impact on settling velocity



Pilot plant Epe in the winter <10 °C

SVI depends also on water characteristics

$$SV = \frac{g}{18} \cdot \frac{\rho_p - \rho_w}{\rho_w} \cdot \frac{d_p^2}{v_w}$$

$SV =$ settling velocity of a single particle $\left[\frac{m}{s}\right]$

$d_p =$ particle diamter $[m]$

$\rho_p =$ density of the particle $\left[\frac{kg}{m^3}\right]$

$p_w =$ denistiy of the fluid $\left[\frac{kg}{m^3}\right]$

$g =$ gravitational constant 9,81 $\left[\frac{m}{s^2}\right]$

$v_w =$ viscosity water $\left[\frac{m^2}{s}\right]$

Settling velocity strongly dependents on temperature

denistiy and viscosity of water at 303K

$p_w = 995$ $\left[\frac{kg}{m^3}\right]$

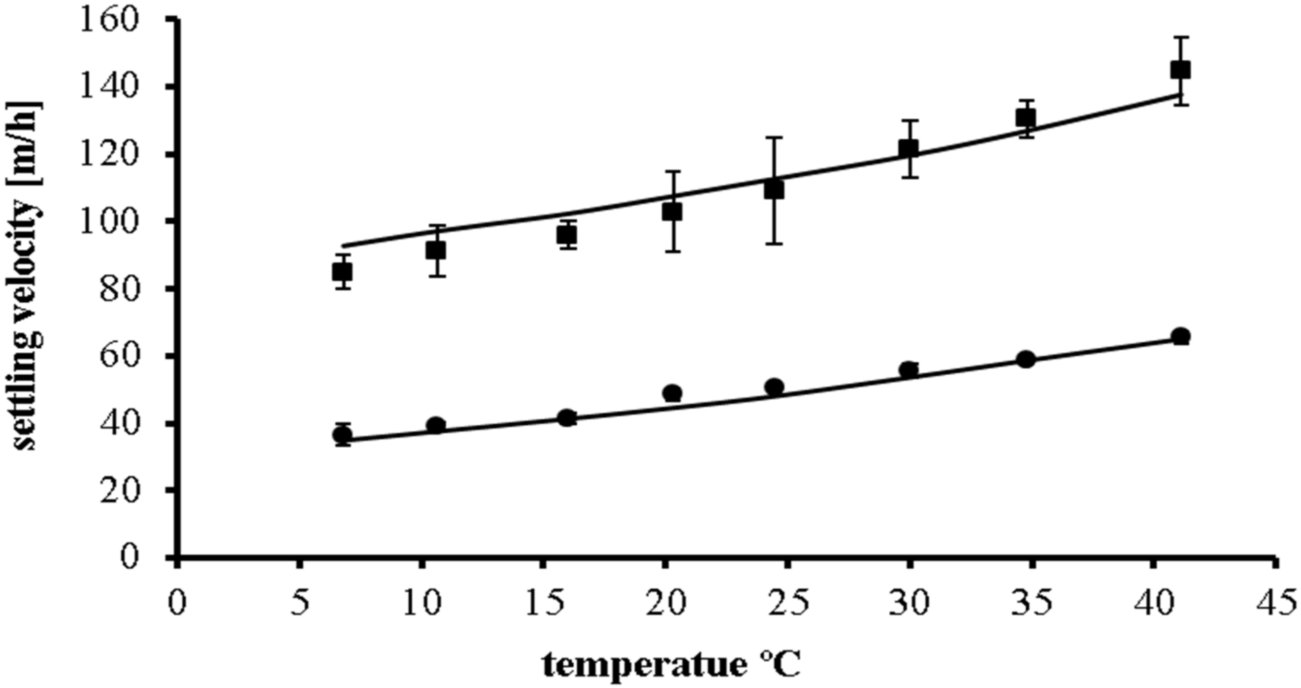
$v_w = 0.8$ $\left[\frac{m^2}{s}\right]$

denistiy and viscosity of water at 278K

$p_w = 1000$ $\left[\frac{kg}{m^3}\right]$

$v_w = 1.5$ $\left[\frac{m^2}{s}\right]$

Physical properties temperature



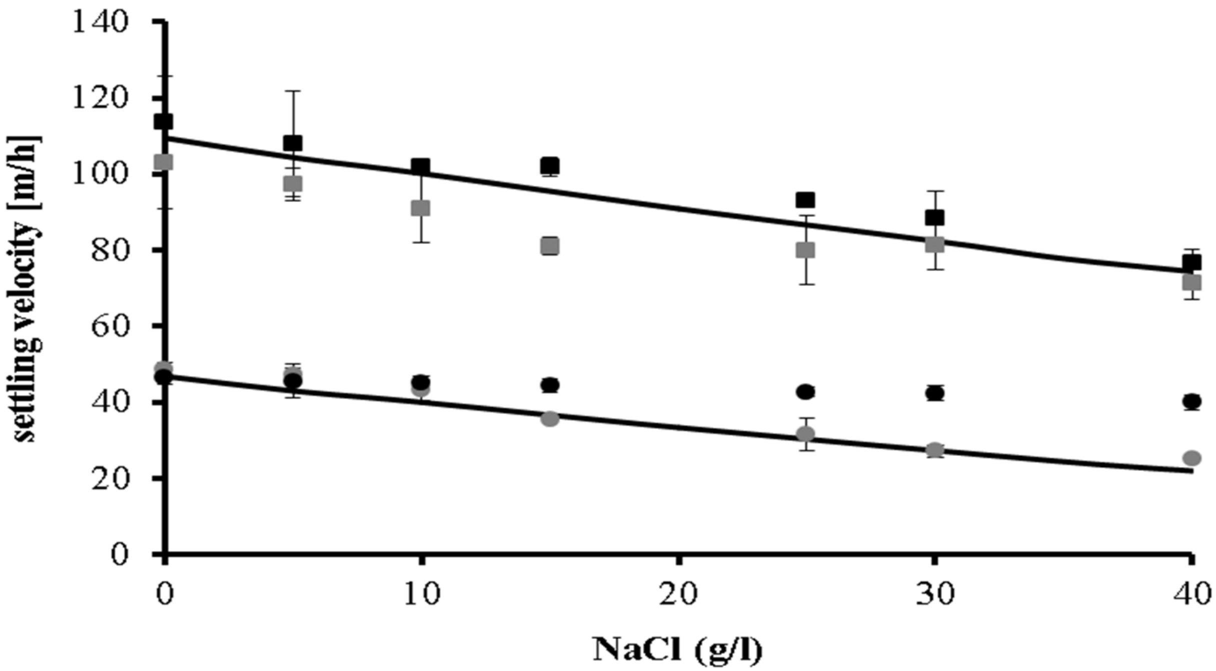
Small granules (●)
Big granules (■)
Theoretical settling velocities (-)

Challenges of aerobic granular sludge

- Not readily adaptable to most existing reactor geometries
- Bio-augmention of granules from side stream in main stream
- Recovery of alginate as valuable raw material (chemical sector, paper and textile industry)
- Phosphate recovery from phosphorous rich stream

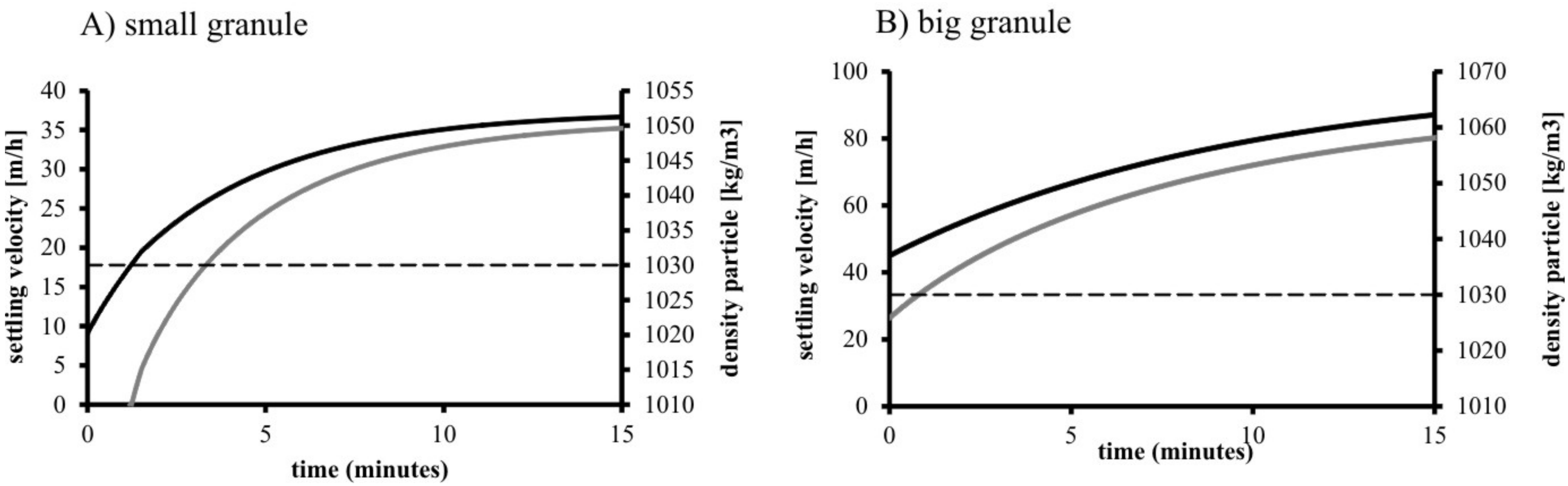

ANY
QUESTIONS
?

Physical properties salt



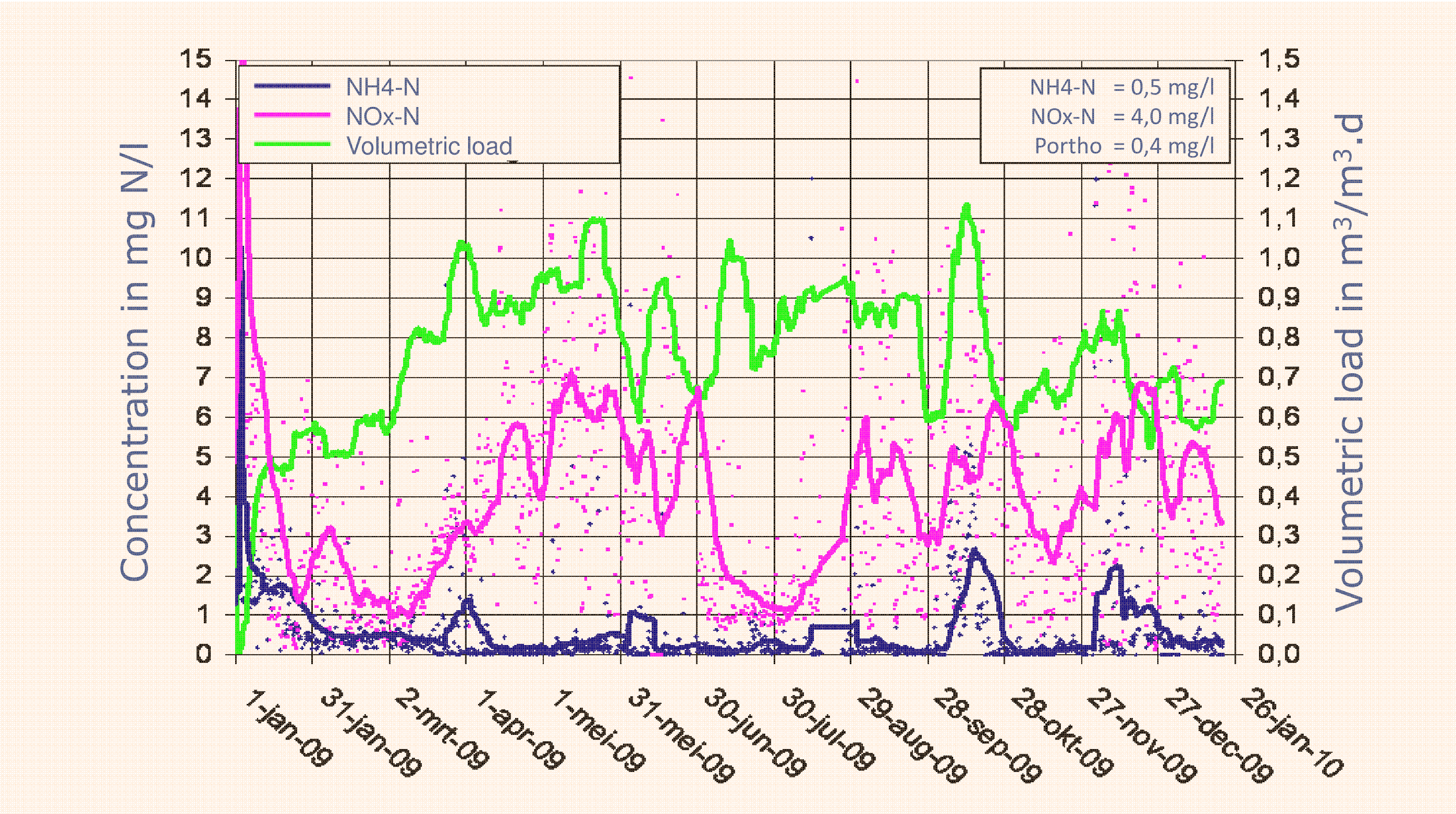
Small granules	(●)
Big granules	(■)
Theoretical settling velocities	(-)
15 minutes pre-incubation	(grey)
24 hours pre-incubation	(black)

Time dependent density increase



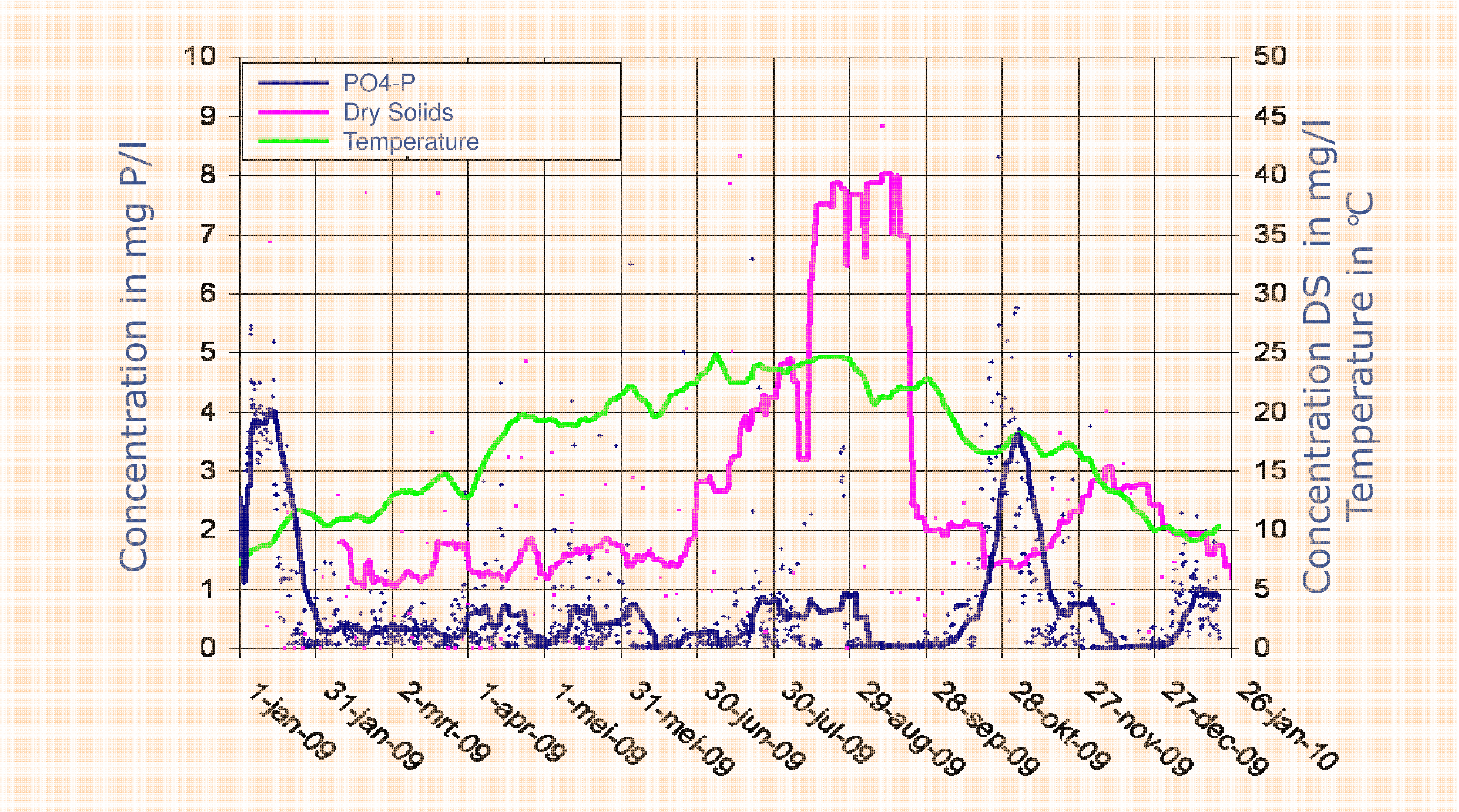
Density (black)
Settling velocity (gray)

Nereda®
N removal Epe



Results Nereda®

P removal Epe pilot plant



Results Nereda®

Sludge sludge characteristics Pilot plant Epe