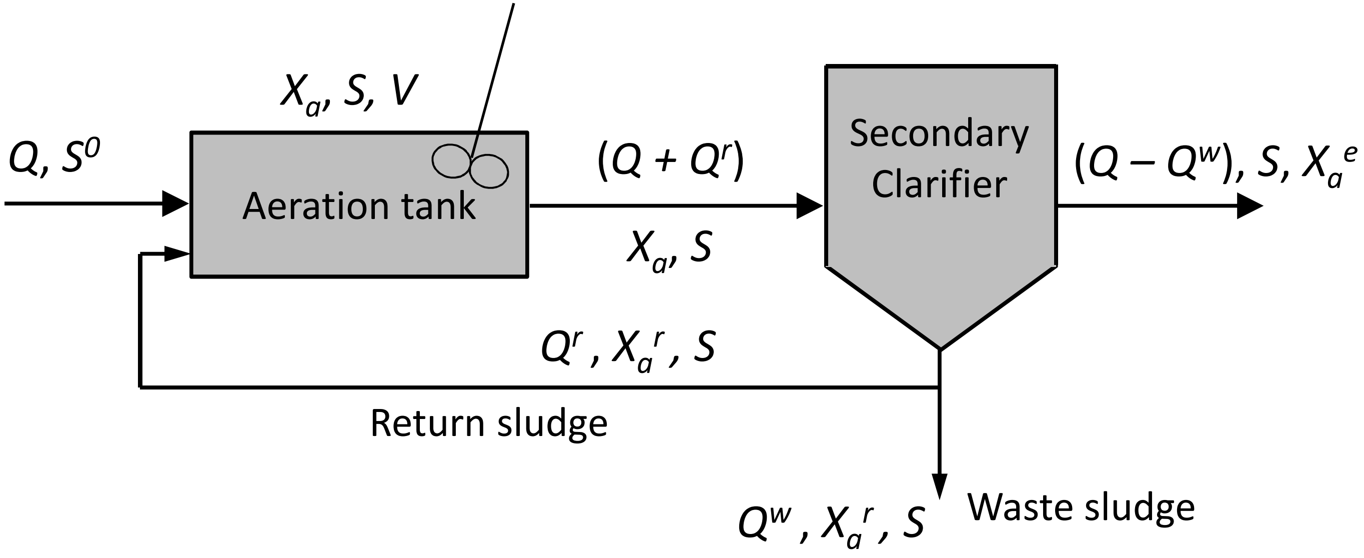
Biological wastewater treatment

Today's lecture

- Conventional activated sludge process
  → Most common approach for BOD removal

- Biological nutrient removal
  - Strategies to improve N & P removal efficiency in the secondary treatment

Analyzing activated sludge process



Remember:

$$S = K\frac{1 + b\theta_x}{\theta_x(Y\hat{q} - b) - 1}$$

$$X_a = \frac{\theta_x}{\theta}\frac{Y(S^0 - S)}{1 + b\theta_x}$$

⇨ SRT a key parameter

Aeration tank & clarifier

Other important design parameters

- **Food-to-microorganism ratio (F/M)**

with respect to TSS:

$$F/M = \frac{Q^0 S^0}{VX}$$

with respect to VSS:

$$F/M_v = \frac{Q^0 S^0}{VX_v}$$

X = total suspended solids (TSS) in aeration tank (mg/L)

X_v = volatile suspended solids (VSS) in aeration tank (mg/L)

- **Volumetric organic loading rate (OLR)**: the amount of BOD or COD applied to the aeration tank volume per day

$$Volumetric\ \ OLR = \frac{Q^0 S^0}{V}$$

Settling problems: Bulking sludge

- Sludge blanket not stable; large quantities of SS carried along with the clarifier effluent
- Exceeding the effluent standard for SS & BOD/COD
- Two principal types of sludge bulking
  - Filamentous bulking: growth of filamentous organisms
  - Viscous bulking: production of excessive amount of extracellular biopolymer

Filamentous vs. viscous bulking

- **Filamentous bulking**
  - Bacteria form filaments of single-cell organisms that attach end-to-end, and the filaments protrude out of the sludge floc
  - Filamentous bacteria are competitive at low DO, low organic conc., low nutrient conc. → need control of these variables!

- **Viscous bulking**
  - Results in a sludge with a slimy, jellylike consistency
  - Biopolymers are hydrophilic → contains significant amount of water in the floc → low density, poor compaction
  - Found at nutrient-limited systems and at a very high F/M ratio

Settling problems: Nocardioform foam

- “Nocardioform” bacteria have hydrophobic cell surfaces and attach to air bubbles, causing foaming
- Thick foam (0.5~1 m) of brown color forms
- Can occur in diffused aeration systems and also in anaerobic treatment systems
- Major solutions
  - Avoid trapping foam in the aeration tank effluent
  - Surface wasting of activated sludge
  - Avoid the recycle of skimmings

Settling problems: Rising sludge

- Rising of sludge having relatively good settling properties due to gas formation
- Gas commonly produced: N_2
- Gas bubble attaches to the sludge and increases buoyant force
- Solutions
  - Increasing the return activated sludge withdrawal rate from the clarifier (less residence time of sludge in the clarifier)
  - Temporally decreasing the rate of flow of aeration liquor into the clarifier
  - Increasing the speed of the sludge collecting mechanism
  - Decreasing the SRT (prevent nitrification) or add an anoxic reactor (complete nitrification-denitrification)

Biological oxidation of nitrogen

- Necessity for NH_4-N & NO_2-N oxidation
  - The effect of ammonia on receiving water with respect to DO concentrations and fish toxicity
  - The need to provide nitrogen removal to control eutrophication
  - The need to provide nitrogen control for water-reuse applications

- **Nitrification**
  - Two-step biological process: NH_4-N → NO_2-N & NO_2-N → NO_3-N
  - The first step [NH_4-N → NO_2-N] is termed as “nitritation”
  - Different type of microorganisms are involved for each step

Nitrification: Processes & microbiology

- Process
  - Both suspended & attached growth applicable
  - Suspended growth nitrification processes
    - Note nitrifying bacteria are less competent than aerobic heterotrophs → need maintaining low BOD conc. to activate them!
    - So: operate the reactor **at higher SRT** than what's needed for BOD removal
- Microbiology
  - Ammonia-oxidizing bacteria (AOB) & nitrite-oxidizing bacteria (NOB) --- aerobic chemoautotrophs
  - AOBs: *Nitrosomonas* (+*Nitrosospira*)
  - NOBs: *Nitrobacter* (+*Nitrococcus, Nitrospina, Nitrospira*)

Nitrification stoichiometry

AOB (nitration): $2NH_4{}^+ + 3O_2 \rightarrow 2NO_2{}^- + 4H^+ + 2H_2O$

NOB: $2NO_2{}^- + O_2 \rightarrow 2NO_3{}^-$

Overall: $NH_4{}^+ + 2O_2 \rightarrow NO_3{}^- + 2H^+ + H_2O$

Note: This is the stoichiometry for ***energy reaction*** *(**NOT** considering biomass growth)*

- Oxygen requirement: 2 mole O_2/1 mole $NH_4{}^+$
  = 4.57 g O_2/g NH_4-N oxidized
- Alkalinity consumption: 2 eq alkalinity/1 mole $NH_4{}^+$
  = 7.14 g Alk as $CaCO_3$/g NH_4-N oxidized
- Nitrification cell yield: 0.10~0.15 for AOB & 0.04~0.07 for NOB
- Considering biomass production, the O_2 requirements and alkalinity consumption is slightly less than the calculated values above (**why??**)

Nitrification stoichiometry

ex) Assuming Y=0.12 g VSS/g NH_4-N for AOB and Y=0.04 g VSS/g NO_2-N for NOB, the overall stoichiometry is:

$$NH_4(HCO_3) + 0.9852Na(HCO_3) + 0.0991CO_2 + 1.8675O_2 \rightarrow$$

$$0.01982C_5H_7O_2N + 0.9852NaNO_3 + 2.9232H_2O + 1.9852CO_2$$

→ 1.8675 mole O_2/1 mole NH_4^+

1.9852 eq Alk/1 mole NH_4^+

Environmental factors affecting nitrification

- **DO concentration**
  - Nitrifying bacteria are more sensitive to DO than heterotrophs
  - Nitrite oxidation is inhibited more at low DO than ammonia oxidation → elevated NO_2-N concentration at low DO

- **pH**
  - Optimum at pH of 7.5~8.0
  - Ammonia oxidation rate reduces significantly at pH<7.0
  - Possibly due to the reduction of free ammonia (NH_3) concentration
  - **Sufficient alkalinity is needed!**
  - For wastewater with high NH_4^+ concentrations and low alkalinity, addition of alkalinity may be needed (lime, soda ash, $NaHCO_3$, …)

Environmental factors affecting nitrification

- **Toxicity**
  - AOB is sensitive to a wide range of organic & inorganic compounds
  - Show significantly reduced ammonia oxidation rate in the presence of toxic substances

- **Free ammonia & nitrous acid inhibition**
  - NH_3-N & HNO_2
  - High pH: NH_3-N ↑ / low pH: HNO_2 ↑

Denitrification

- **Biological reduction of nitrate (NO_3^-) or nitrite (NO_2^-) to nitrogen gas (N_2)**

- **Denitrification required**
  - To complete the biological nitrogen removal process
  - Otherwise, accumulation of NO_3-N: health threats!
  - "Blue baby syndrome"
  - Korean regulation: < 10 mg NO_3-N/L

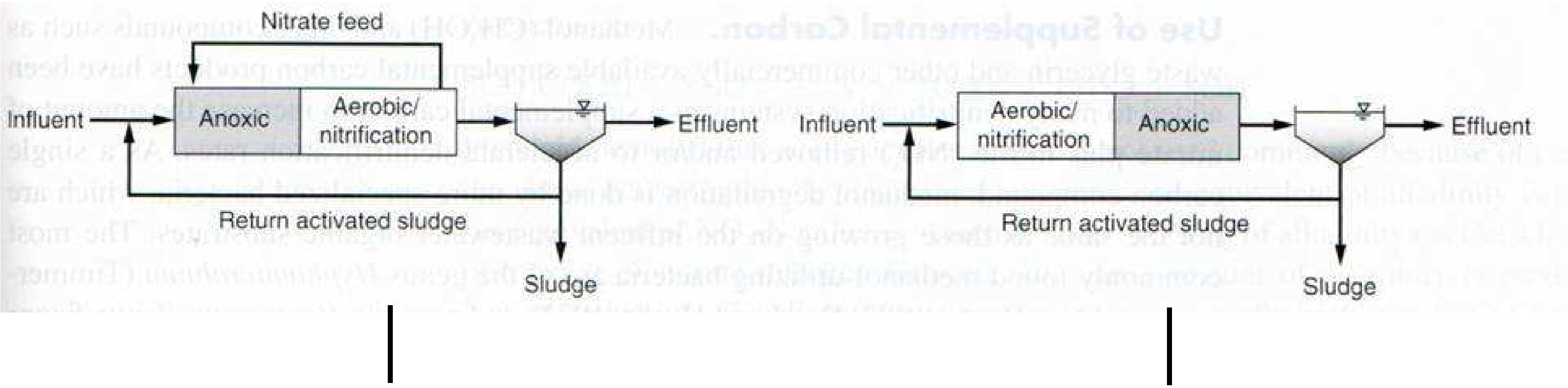
- **Usually by heterotrophic bacteria**
  - Wide range of heterotrophs – mostly facultative aerobes
  - Some autotrophs are capable of nitrate/nitrite reduction
    - Use Fe^0, Fe^{2+}, S^{2-}, S^0, …, or NH_4^+

Denitrification

- Two modes of nitrate removal in biological processes
  - **Assimilatory nitrate reduction**
    - Reduction of NO_3-N to NH_4-N for use in cell synthesis when NH_4-N is not available
    - Independent of DO concentration
  - **Dissimilatory nitrate reduction**: much more significant!
    - Nitrate/nitrite serves as an electron acceptor
    - When DO is absent or limited
    - Mostly facultative bacteria
    - Nitrate reduction proceeds through a series of intermediate products:

$$NO_3{}^- \rightarrow NO_2{}^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$$

Denitrification processes



- **Preanoxic denitrification**
  - Electron donor provided by influent
  - MLE (Modified Ludzak-Ettinger) process: most common for biological nitrogen removal in municipal wastewater treatment
- **Postanoxic denitrification**
  - BOD not available in anoxic reactor: denitrification by endogenous decay
  - Much slower rate than preanoxic
  - Often external carbon source is added (e.g. methanol, acetate)

Denitrification Stoichiometry

Wastewater: $C_{10}H_{19}O_3N + 10NO_3^{\ -} \rightarrow 5N_2 + 10CO_2 + 3H_2O + NH_3 + 10OH^-$

Methanol: $5CH_3OH + 6NO_3^{\ -} \rightarrow 3N_2 + 5CO_2 + 7H_2O + 6OH^-$

Acetic acid: $5CH_3COOH + 8NO_3^{\ -} \rightarrow 4N_2 + 10CO_2 + 6H_2O + 8OH^-$

- **Production of alkalinity**
  - 3.57 g Alk as $CaCO_3$ produced per g NO_3-N (or NO_2-N) reduced
  - 50% of alkalinity consumed by nitrification can be recovered

Denitrification: Organic substrate requirements

- A sufficient amount of organic substrate (e^- donor) should be available
  - **bsCOD or BOD as an important design parameter**
  - **Sources of e^- donor for denitrification**
    1) bsCOD in the influent
    2) bsCOD produced during biological hydrolysis
    3) bsCOD produced during endogenous decay
    4) External source such as methanol or acetate
  - ~4 g BOD required per g NO_3-N reduced
    - actual requirement depending on operating conditions and the type of e^- donor
  - Especially important to determine the BOD requirements when external carbon source is provided

Simultaneous nitrification and denitrification

- In activated sludge floc (suspended growth) or biofilm (attached growth)
- Local conditions in the floc or biofilm may be different from bulk liquid
- **High DO at the exterior and low DO inside →** conditions for nitrification and denitrification may develop in a single floc or biofilm
- Can be significant if optimal conditions are developed

Anammox process

- **An**aerobic **amm**onia **ox**idation
- **Anaerobic oxidation of ammonia to produce nitrogen gas**

$$NH_4{}^+ + NO_2{}^- \rightarrow N_2 + H_2O$$

e⁻ donor *e⁻ acceptor*

- **Requires aerobic nitritation of ammonia to NO_2^-** for the process to occur (~55% conversion of NH_4-N to NO_2-N)

- **By autotrophic bacteria**

  → No organic carbon consumption during the process

Anammox process

$$NH_4{}^{+} + NO_2{}^{-} \rightarrow N_2 + H_2O$$

- **Proposed metabolic model** (Van de Graaf et al., 1997)
  1) Reduction of nitrite to hydroxylamine (NH_2OH)
  2) Condensation of hydroxylamine with ammonium to hydrazine (N_2H_4)
  3) Oxidation of hydrazine to nitrogen gas

- **Some formation of NO_3-N from NO_2-N**
  - To provide the reducing power to fix CO_2

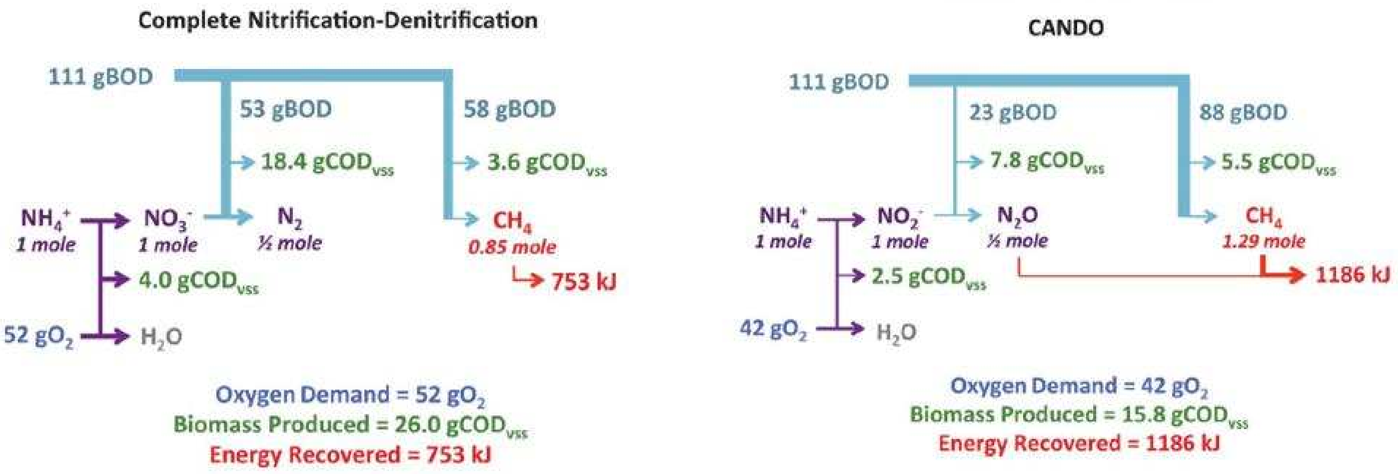
$$CO_2 + 2NO_2{}^{-} + H_2O \rightarrow CH_2O + 2NO_3{}^{-}$$

- **Overall reaction** (Strous et al., 1999)

$$1.0NH_4{}^{+} + 1.32NO_2{}^{-} + 0.066HCO_3{}^{-} + 0.13H^{+}$$
$$\rightarrow 1.02N_2 + 0.26NO_3{}^{-} + 0.066CH_2O_{0.5}N_{0.021} + 2.03H_2O$$

CANDO process

- **C**oupled **A**erobic-anoxic **N**itrous **D**ecomposition **O**peration
- A recently proposed process (Scherson et al., Energy Environ. Sci., 2013)
- Three-step process
  1) Partial nitrification of NH_4^+ to NO_2^- (same as the prelim. step for AMMANOX)
  2) **Partial anoxic reduction of NO_2^- to N_2O**
  3) N_2O conversion to N_2 with energy recovery (e.g., use as an oxidant for $CH_4 \rightarrow CO_2$)
- Pilot-scale demonstration underway

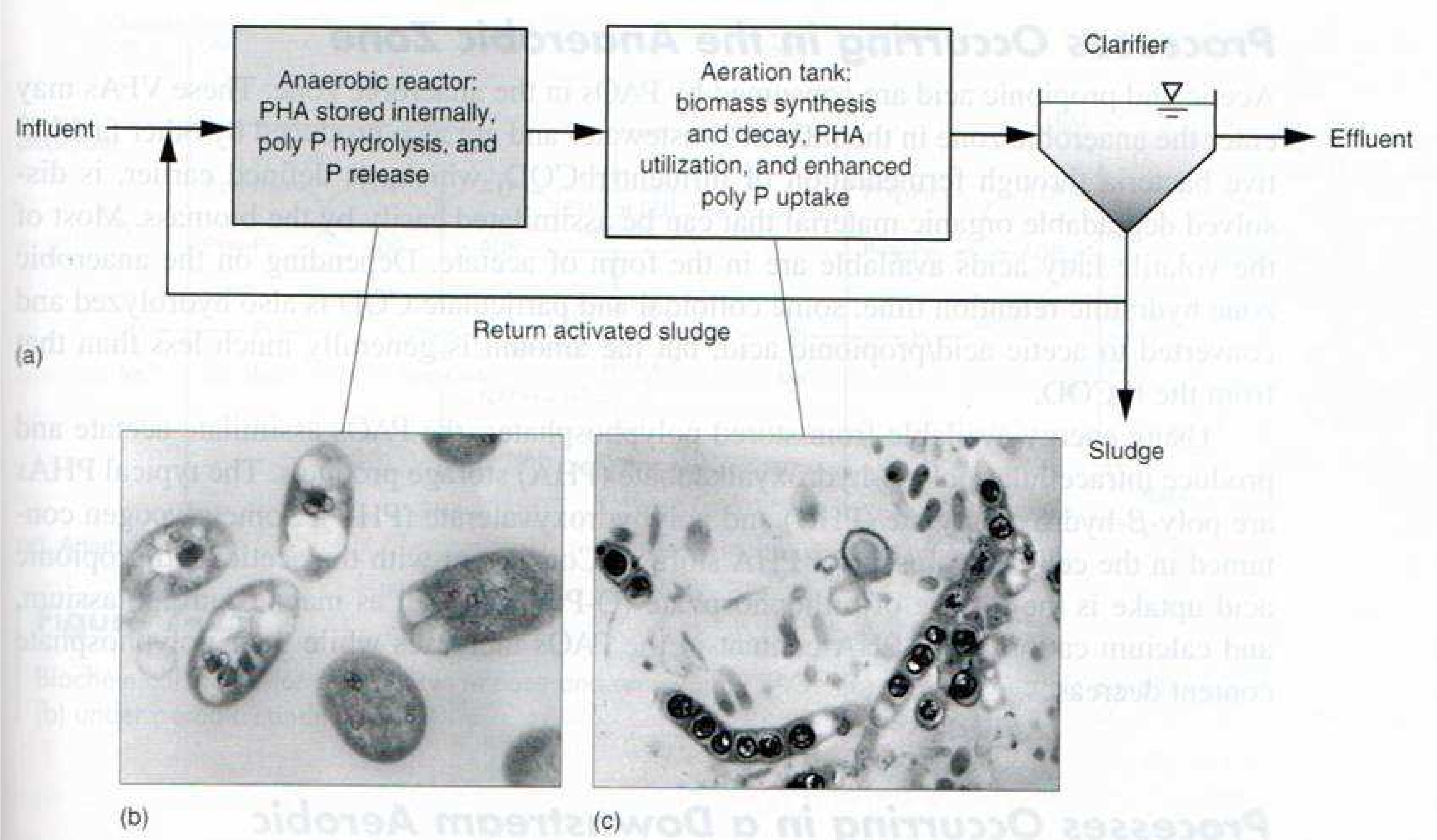


Scherson et al., 2013

Enhanced biological P removal

- Involves incorporation of P in the biomass produced in the treatment system and subsequent removal of the biomass as waste sludge
- Biomass of heterotrophic bacteria contains ~0.015 g P/g VSS
  - Insufficient to remove P from influent wastewater (only 10~20% of total)
- Use **phosphorus accumulating organisms (PAOs)** for ***enhanced*** **biological phosphorus removal (EBPR)**
- Reduced chemical costs and less sludge production compared to chemical precipitation

Enhanced biological P removal



EBPR: Process description

- Place an anaerobic tank ahead of the aeration tank
  - Provide selectivity for growth of PAOs
- In the anaerobic tank, PAOs consume energy stored in the form of polyphosphates
  - The energy generated is used to convert volatile fatty acids into carbohydrate storage products (PHA)
- In the aerobic tank, PAOs consume COD & stored PAH for biomass growth
  - Use some of the energy for enhanced P uptake to store polyphosphates
- So:
  - Anaerobic tank: PHA accumulation & P release
  - Aerobic tank: excessive P uptake & PHA utilization
- PAOs form very dense floc with good settleability – additional benefit

EBPR: Process description

- **Process occurring in the anaerobic zone**
  - Volatile fatty acids (VFAs) are produced by fermentation
  - VFAs are assimilated by PAOs into PHAs by energy available from stored polyphosphates
    - Typical PHAs: poly-β-hydroxybutyrate (PHB) & polyhydroxyvalerate (PHV)
    - Some glycogen contained in the cell is also used

- **Processes occurring in the aerobic/anoxic zone**
  - Stored PHA is metabolized to provide energy for cell growth
  - Some glycogen is produced from PHA metabolism
  - Soluble orthophosphate in solution in taken up by PAOs to form polyphosphates in the existing cells and the new cells
  - Portion of the biomass is wasted → P removal
  - The process can occur in the anoxic zone as well (NO_3^- or NO_2^- as e^- acceptors)