Chapter 11. Phosphorus Removal

All the figures and tables in this material are from the reference below unless specified otherwise.
Reference: Bruce E. Rittmann and Perry L. McCarty, "Environmental Biotechnology: Principles and Applications", McGraw-Hill, 2001.

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Intro: Phosphorus Removal

√ Phosphorus removal

- Phosphorus is an essential macronutrient that spurs the growth of photosynthetic algae and cyanobacteria, leading to accelerated eutrophication of lake.

- Three microbiological approaches to remove phosphorus:

  - Normal phosphorous uptake into biomass
  - Precipitation by metal-salts addition to a microbiological process
  - Enhanced biological phosphorus uptake into biomass

11.1. Normal Phosphorus Uptake into Biomass

- The stoichiometric formula for biomass can be modified to include this amount of P

$$C_5H_7O_2NP_{0.1}$$

(P takes over 2.67% of the cell mass)

- A steady-state mass balance on total P in the activated sludge process

$$0 = QP^0 - QP - Q^w X_v^w (0.0267 \text{ g P/g VSS})$$

- Sludge wasted from the process removes P in proportion to the mass rate of sludge VSS wasted ($Q^w X_v^w$).

$$P = \frac{QP^0 - Q^w X_v^w (0.0267)}{Q} = P^0 - \frac{Q^w X_v^w (0.0267)}{Q}$$

$$Q^w X_v^w = Y_n Q(\Delta \text{BOD}_L) \qquad Y_n = Y \frac{1 + (1 - f_d) b\theta_x}{1 + b\theta_x}$$

- Y_n decreases with increasing θ_x due to the cell decay.

11.1. Normal Phosphorus Uptake into Biomass

$$P = P^0 - \frac{(0.0267)Y(1 + (1 - f_d)b\theta_x)(\Delta \mathrm{BOD}_L)}{1 + b\theta_x}$$

Table 11.1 Effects of SRT and BOD_L removal on the effluent P concentration when the influent P concentration is 10 mg P/l

BOD_L removal, mg BOD_L/l	Effluent PO_4-P Concentration, mg/l			
	3 d	6 d	15 d	30 d
100	9.0	9.1	9.4	9.5
300	7.0	7.4	8.1	8.5
500	5.0	5.7	6.8	7.5
1,000	0	1.4	3.6	5.1

Note: Y = 0.46 mg VSS_a/mg BOD_L, f_d = 0.8, b = 0.1/d, and biomass P content = 2.67 percent.

11.2. Precipitation by Metal–Salts Addition to a Biological Process

- Salts of Al^{3+} or Fe^{3+} can be added directly to the wastewater as it enters or leaves the bioreactor.

$$AlPO_{4(s)} = Al^{3+} + PO_4^{3-} \qquad pK_{so} = 21$$

$$FePO_{4(s)} = Fe^{3+} + PO_4^{3-} \qquad pK_{so} = 21.9 \text{ to } 23$$

Very low solubility constants

- However, competing acid/base and complexation reactions make the chemistry complicated.

$$HPO_4^{2-} = H^+ + PO_4^{3-} \qquad pK_{a,3} = 12.3$$

$$H_2PO_4^- = H^+ + HPO_4^{2-} \qquad pK_{a,2} = 7.2$$

$$H_3PO_4 = H^+ + H_2PO_4^- \qquad pK_{a,1} = 2.1$$

$$Fe^{3+} + OH^- = FeOH^{2+} \qquad pK_1 = 11.8$$

$$FeOH^{2+} + OH^- = Fe(OH)_2^+ \qquad pK_2 = 10.5$$

$$Fe(OH)_2^+ + OH^- = Fe(OH)_3^0 \qquad pK_3 = 7.7$$

$$Fe(OH)_3 + OH^- = Fe(OH)_4^- \qquad pK_4 = 4.4$$

$$Al^{3+} + OH^- = AlOH^{2+} \qquad pK_1 = 9.0$$

$$AlOH^{2+} + OH^- = Al(OH)_2^+ \qquad pK_2 = 9.7$$

$$Al(OH)_2^+ + OH^- = Al(OH)_3^0 \qquad pK_3 = 8.3$$

$$Al(OH)_3 + OH^- = Al(OH)_4^- \qquad pK_4 = 6.0$$

11.2. Precipitation by Metal–Salts Addition to a Biological Process

- **Several factors act to complicate the chemistry and increase the metal-salts addition.**

1. Phosphate forms competing complexes, such as $CaHPO_4$, MgHPO4, and $FeHPO_4^+$. Thus, the fraction of total phosphate that is present as PO_4^{3-} is less than predicted by acid-base chemistry alone.

2. Aluminum and iron form other complexes, particularly with organic ligands, or precipitate as $Al(OH)_{3(s)}$. These reactions reduce the available Al^{3+} and $Fe^{3+.}$

3. Some of the total phosphorus is not orthophosphate, but is tied up in organic compounds.

4. The optimal pH for precipitation may not be compatible with the optimal microbiological activity. The pH cannot be changed so much that metabolic activity is significantly inhibited.

5. The precipitation reaction may be kinetically controlled and not reach its maximum extent, which occurs at equilibrium.

- **Typically, the metal-salts dosage is 1.5 to 2.5 times the stoichiometric amount.**

11.3. Enhanced Biological Phosphorus Removal

√ Enhanced Biological Phosphorus Removal (EBPR)

- Phosphorus removal can be enhanced by polyphosphate-accumulating organisms (PAOs), *Bio-P bacteria.*

- *Bio-P bacteria* are enriched under anaerobic conditions (no electron acceptors).
  - *Bio-P bacteria* utilize intracellular polyphosphate to generate energy under anaerobic conditions.
  - Under anaerobic conditions, *Bio-P bacteria* store electrons in polyhydroxybutyrate (PHB).
  - *Bio-P bacteria* are selectively enriched, more phosphorus is removed in the following aerobic process.

- The *Bio-P bacteria*-enriched biomass removes 2 to 5 times more P than the normal biomass under aerobic conditions.

$$P = P^0 - \frac{(0.0801)Y(1 + (1 - f_d)\,b\theta_x)(\Delta \mathrm{BOD}_L)}{1 + b\theta_x}$$

3 times enriched

11.3. Enhanced Biological Phosphorus Removal

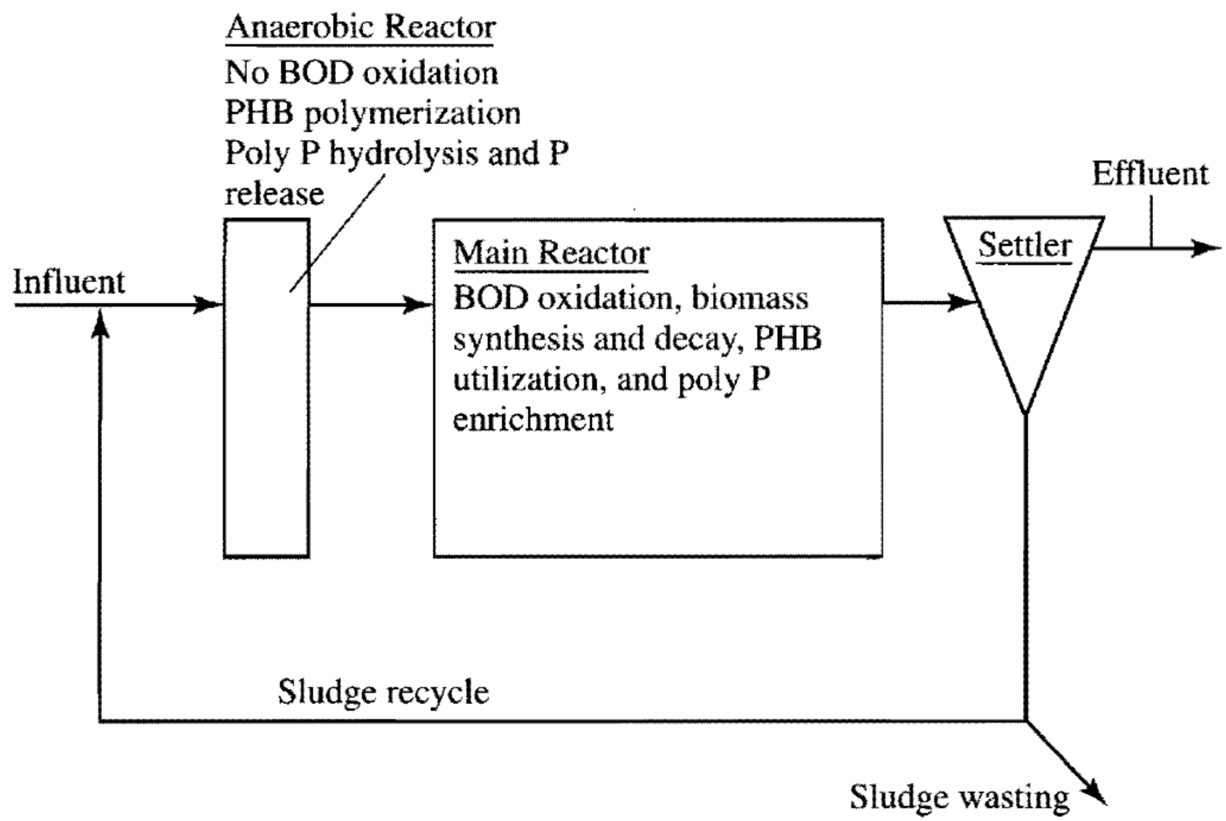

Figure 11.1 Schematic of the required components of an activated sludge process active for enhanced biological phosphorus removal.

11.3. Enhanced Biological Phosphorus Removal

√ Configurations of EBPR

- **Combined processes with nitrogen removal**

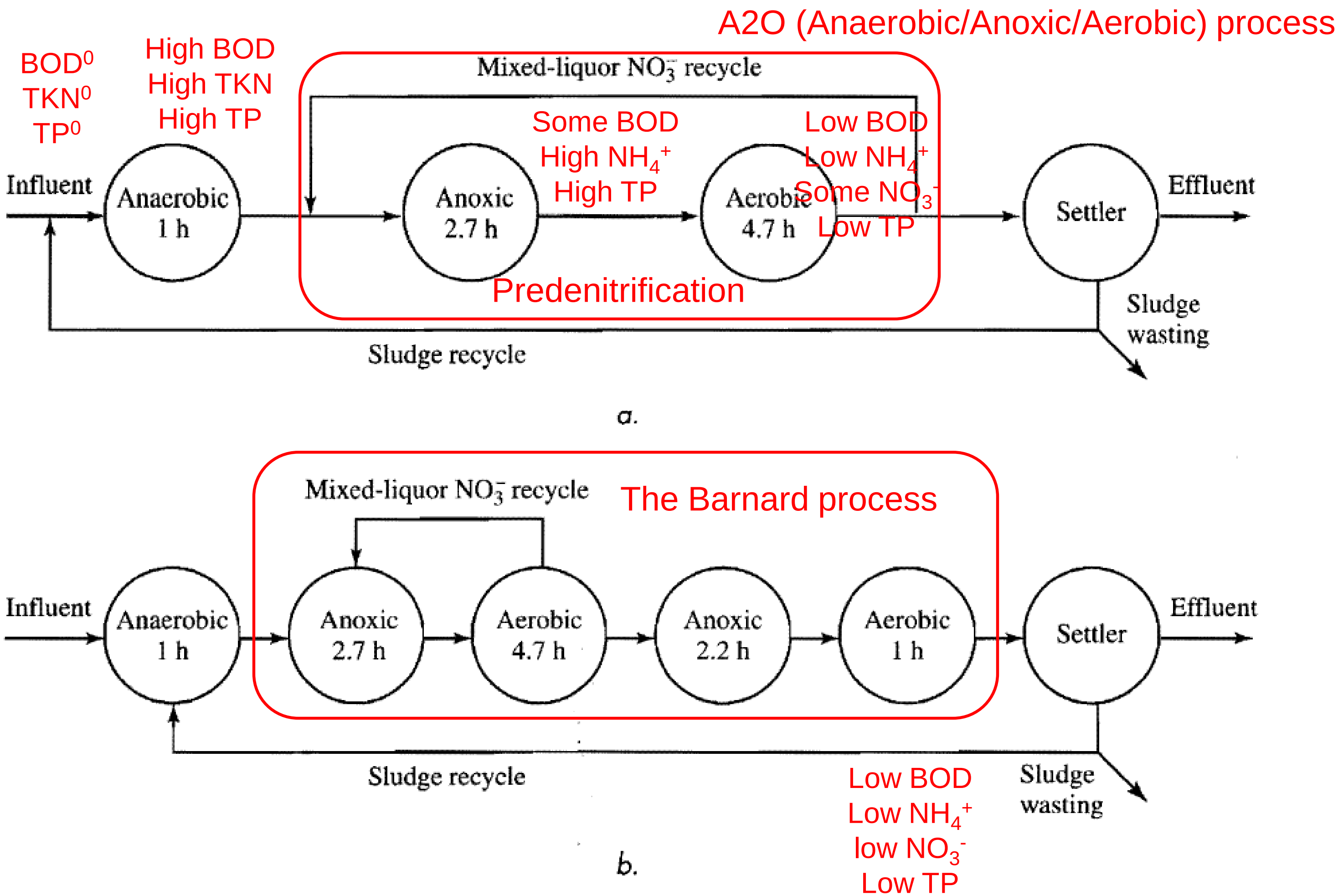

Figure 11.3

11.3. Enhanced Biological Phosphorus Removal

- **Processes to minimize the nitrate recycling: University of Cape Town (UCT) processes**

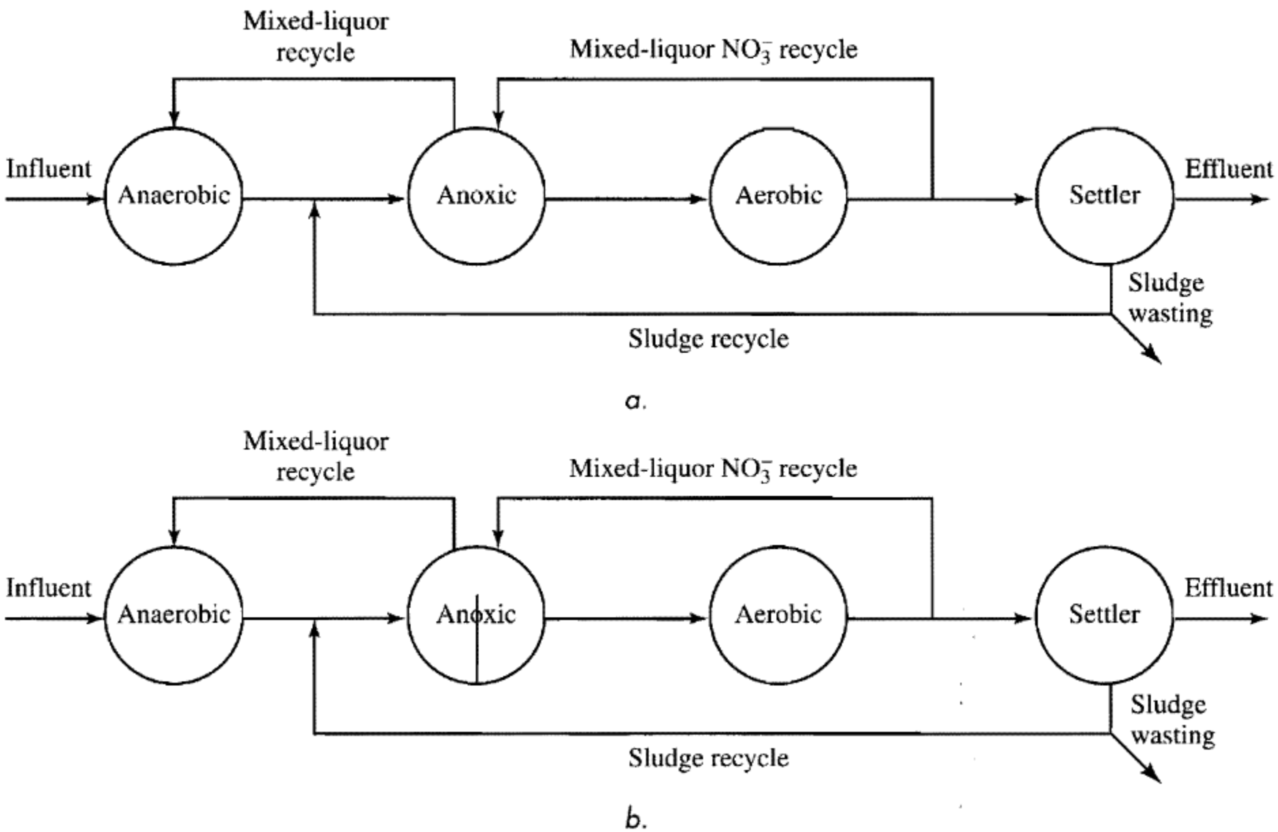

Figure 11.4 Two University of Cape Town (UCT) processes minimize the recycling of NO_3^- to the anaerobic tank. In the modified UCT process *b.*, the anoxic tank is divided into two compartments. The mixed-liquor NO_3^- recycle enters in the downstream part of the anoxic tank, while the mixed-liquor recycle to the anaerobic tank leaves from the upstream part of the anoxic tank. Mixing between the two parts is restricted by a physical barrier.

11.3. Enhanced Biological Phosphorus Removal

- **Combination of Bio-P bacteria with chemical precipitation (*PhoStrip*)**

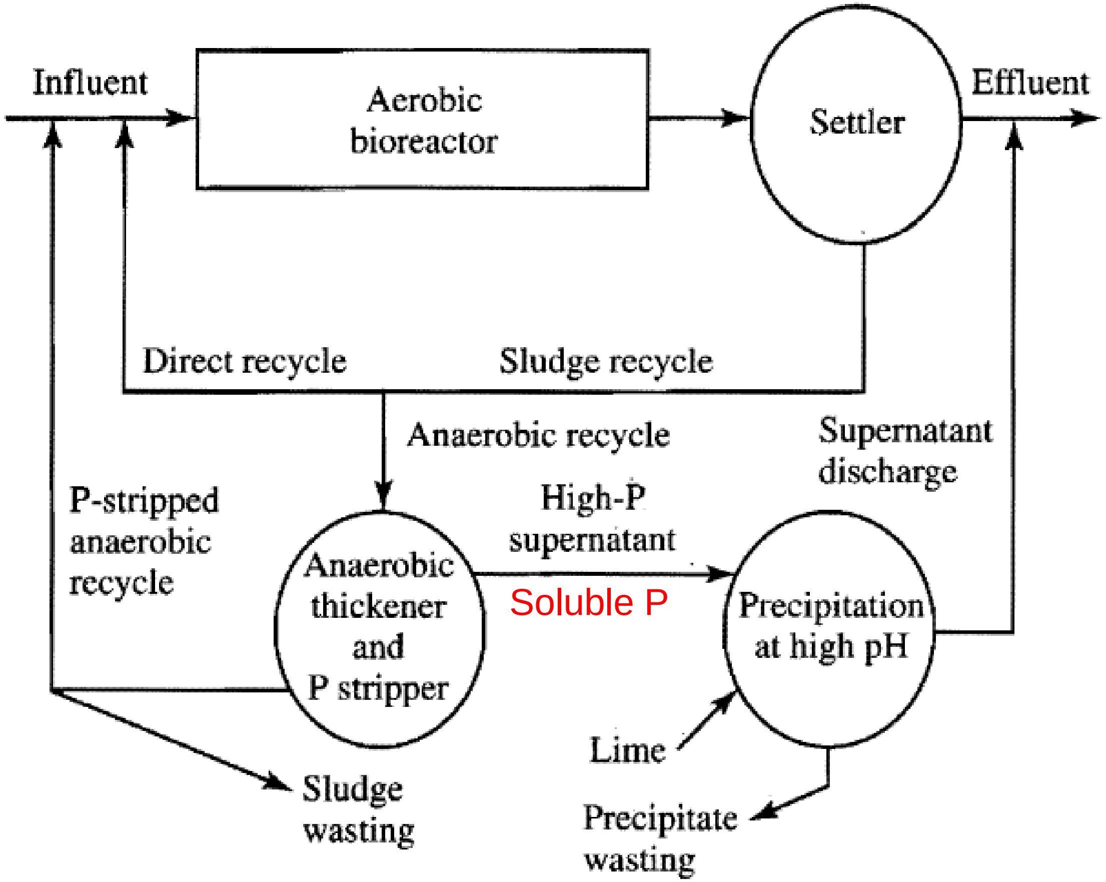

Figure 11.5 Schematic of the PhoStrip process.