Water & Wastewater Treatment-3

- Activated Sludge Process

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공공하수처리시설 · 간이공공하수처리시설의 방류수수질기준

(제3조제1항제1호 관련)

1. 공공하수처리시설의 방류수수질기준

가. 방류수수질기준

구분		생물화학적 산소요구량 (BOD) (mg/L)	화학적 산소요구량 (COD) (mg/L)	부유물질 (SS) (mg/L)	총질소 (T-N) (mg/L)	총인 (T-P) (mg/L)	총대장균군수 (개/mℓ)	생태독성 (TU)
1일 하수처리용량 500㎥ 이상	Ⅰ지역	5 이하	20 이하	10 이하	20 이하	0.2 이하	1,000 이하	1 이하
	Ⅱ지역	5 이하	20 이하	10 이하	20 이하	0.3 이하	3,000 이하	
	Ⅲ지역	10 이하	40 이하	10 이하	20 이하	0.5 이하		
	Ⅳ지역	10 이하	40 이하	10 이하	20 이하	2 이하		
1일 하수처리용량 500㎥ 미만 50㎥ 이상		10 이하	40 이하	10 이하	20 이하	2 이하		
1일 하수처리용량 50㎥ 미만		10 이하	40 이하	10 이하	40 이하	4 이하		

Typical influent: BOD 100~160 mg/L, COD 70~130 mg/L, SS 100~200 mg/L

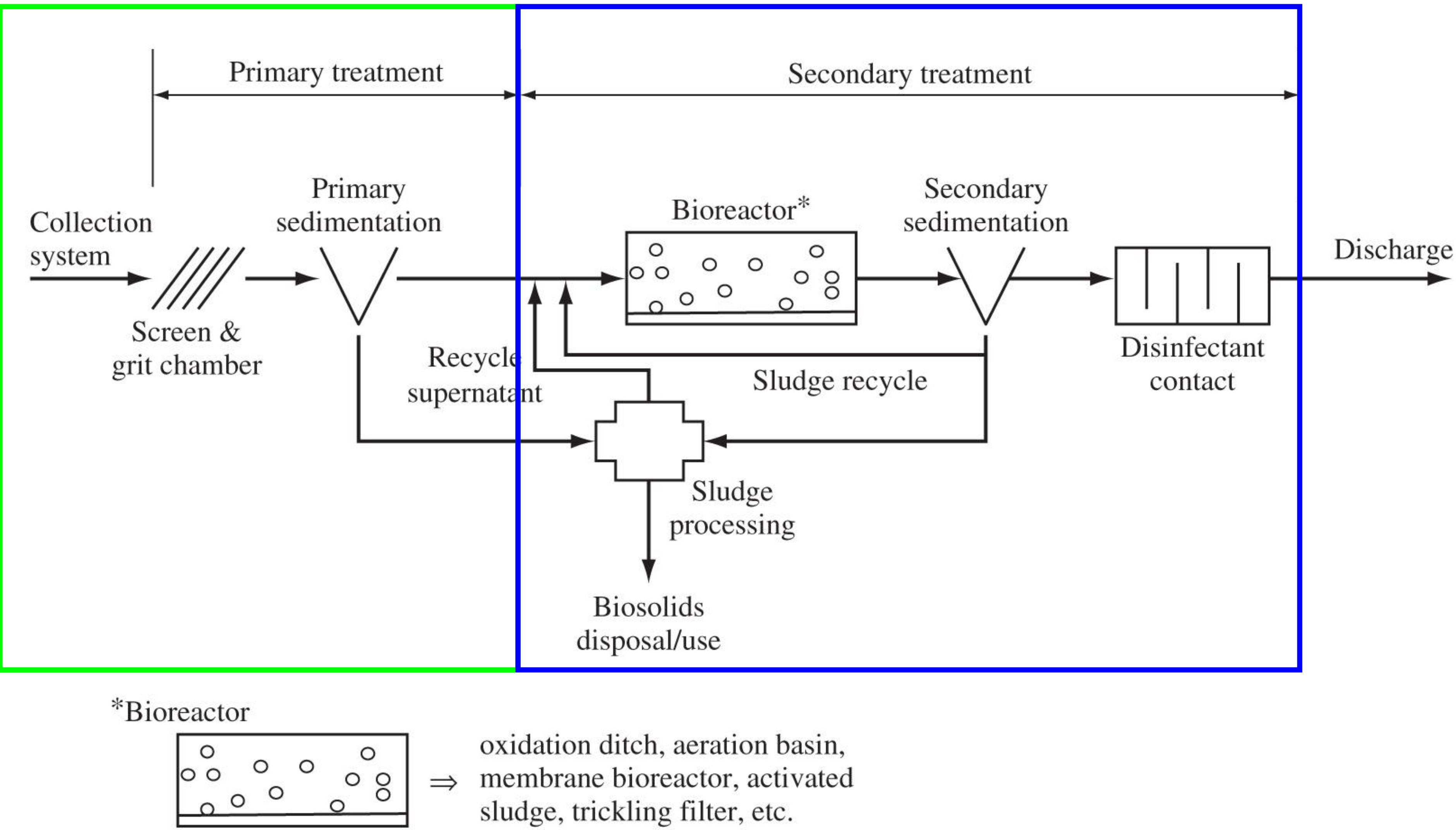
TN 25~50 mg/L, TP 3~5 mg/L

Wastewater Treatment

Sewer is the conscience of a city.

Les Miserables; Victor Hugo, 1862

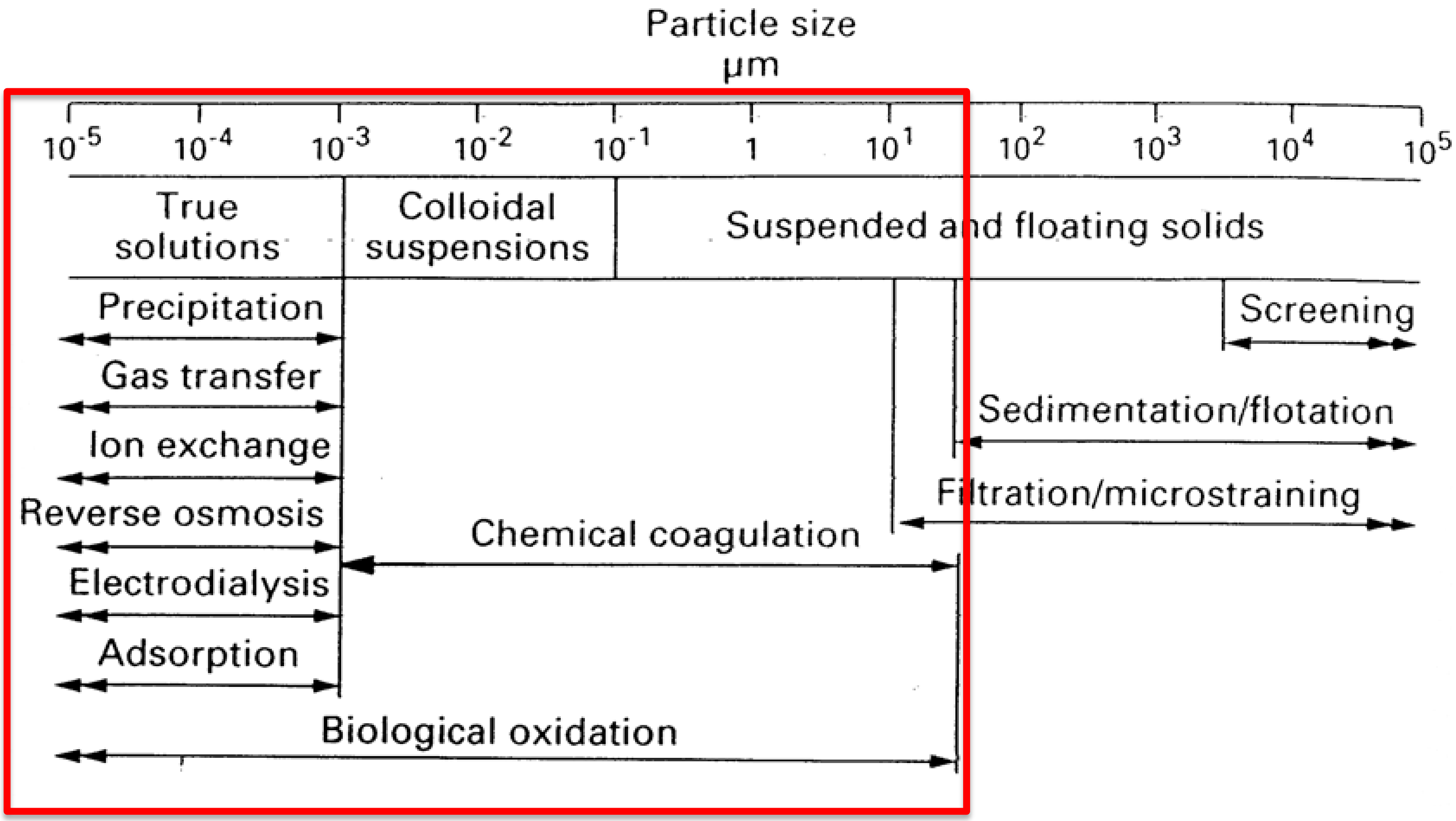
Generic Treatment Process Train



Primary Clarifier

- **Slow settling (HRT 1.5–3 h)**

Pollutant Size and Treatment Method



Secondary Treatment

- **Biological Treatment (activated sludge process)**
  - First goal is to remove BOD from solution.
  - Some of it is mineralized to CO_2, and some of it is converted to biomass (sludge) and discarded.

Organics (BOD) + $O_2 \rightarrow$ Bacteria + CO_2 + H_2O + NH_3

  - Bacteria concentration is measured as Volatile Suspended Solids (VSS)
  - Measure first the total suspended solids (TSS) by filtration and drying, and the inorganic (fixed) content (FSS) as the residue left after burning TSS at 500˚C.
  - Organic content (VSS) converts to CO_2 and is calculated as the difference (VSS = TSS-FSS)

Microbial Growth Kinetics

- First Order!!!! (exponential growth)

  Binary Fission (1 → 2 → 4 → 8 → 16)

$$r_g = \frac{dX}{dt} = \mu X$$

r_g = microbial mass growth rate
X = concentration of organisms (as VSS/L)
μ = specific biomass growth rate coefficient (t^{-1})

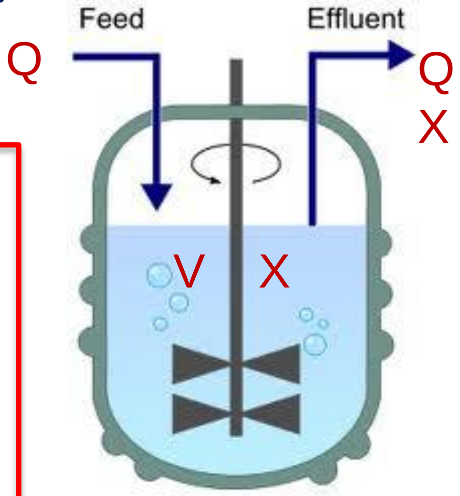
Note, μ depends on the substrate concentration

Example

- *E. coli* growing on glucose, batch system
  X_o = 1000, X = 100,000 after 90 minutes.
  What is the doubling time?

Example

- *E. coli* is now growing in a steady-state chemostat (CSTR). What is the doubling time?



$\theta = V/Q$
(HRT)

Stead state mass balance on biomass

Out = In + Growth

$\Rightarrow Q\,X = 0 + V\,(dX/dt) = V\,(\mu\,X)$

$\Rightarrow Q = V\,\mu$

$\Rightarrow \mu = Q/V = 1/\theta$

At any time, biomass present in reactor = VX (constant, SS)

In a time $t = \theta$, biomass leaving reactor = $QX\,\theta = VX$

This is the same amount that was present at $t = 0$

Thus, biomass doubles in $t = \theta$ and since $\theta = 1/\mu$, $t_d = 1/\mu$

Monod Equation: Growth Rate

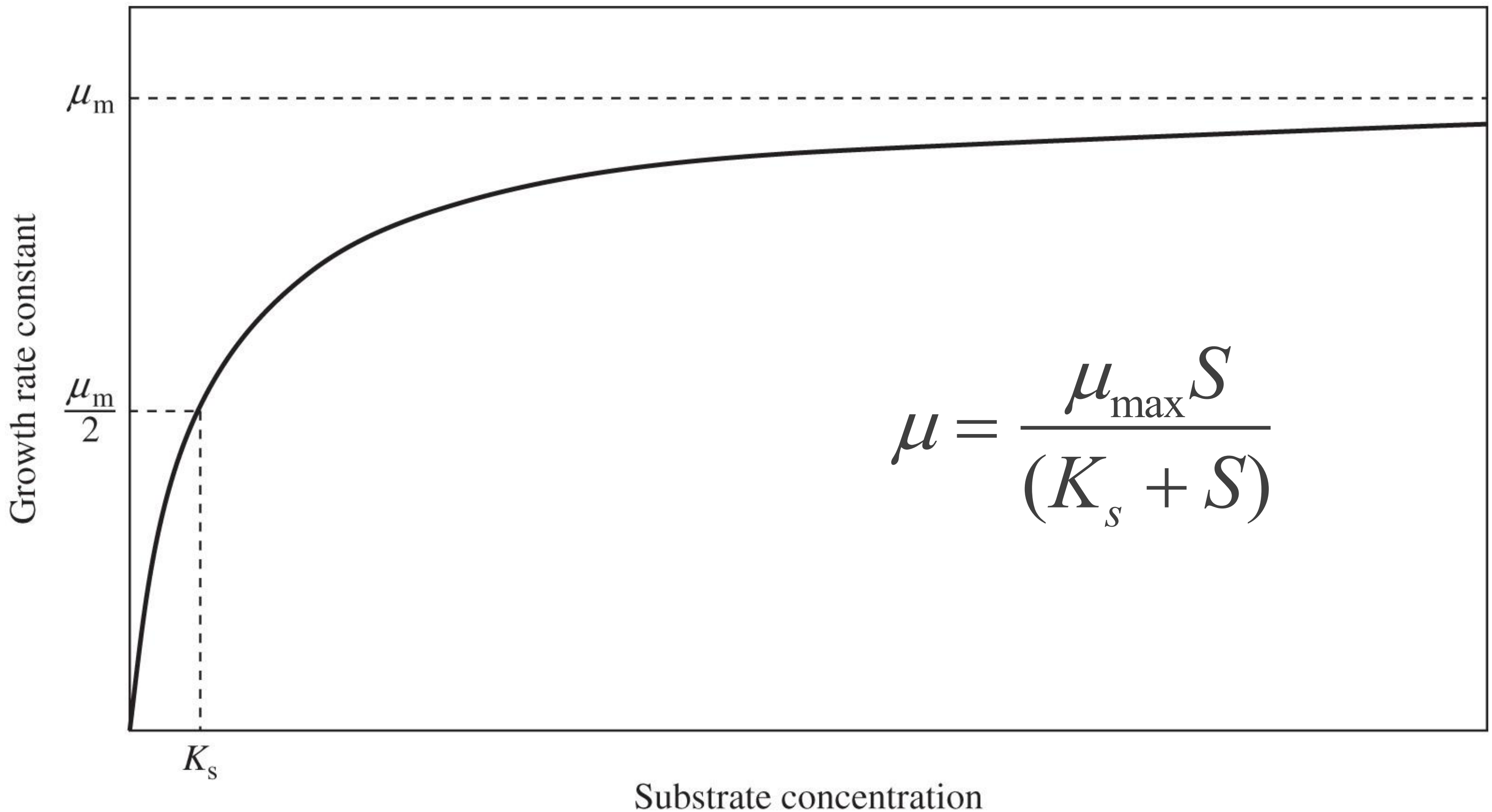
- μ is not constant, depends on substrate concentration
- Substrate = 0 then growth = 0
- Growth rate increases with substrate concentration, until you reach metabolic limits

Thus:

$$\mu = \frac{\mu_{\max} S}{(K_s + S)}$$

μ_{max} = maximum specific growth rate (t^{-1})
S = substrate concentration (as mg BOD_5/L)
K_s = half-velocity constant ([S] when half m_{max} is achieved)

Monod Equation: Growth Rate



$$\mu = \frac{\mu_{max} S}{(K_s + S)}$$

μ

S

Microbial Growth Rate

- Combining previous two equations:

$$r_g = \mu X = \frac{\mu_{\max} XS}{(K_s + S)}$$

r_g = microbial mass growth rate
X = concentration of organisms (as VSS/L)
μ_{max} = maximum specific growth rate (t^{-1})
S = substrate concentration (as mg BOD_5/L)
Ks = half-velocity constant

Rate of Substrate Consumption

√ **How fast is BOD_5 removed?**

- Termed SUBSTRATE UTILIZATION:

$$r_{su} = \frac{dS}{dt} = \frac{-r_g}{Y}$$ (i.e., growth rate = Y × utilization rate)

r_{su} = rate of substrate utilization
r_g = mass growth rate
Y = Yield coefficient = $-\Delta X/\Delta S$
(biomass (VSS) grown per BOD_5 consumed)

Rate of Substrate Consumption

- The maximum specific growth rate μ_{max} is related by the Yield Coefficient (Y = biomass produced per waste consumed) to the maximum specific substrate utilization constant, *k:*

$$k = \frac{\mu_{\max}}{Y}$$

- Combining equations:

$$r_{su} = \frac{dS}{dt} = \frac{-\mu_{\max} XS}{Y(K_s + S)} = \frac{-kXS}{(K_s + S)}$$

Microbial Death Rate

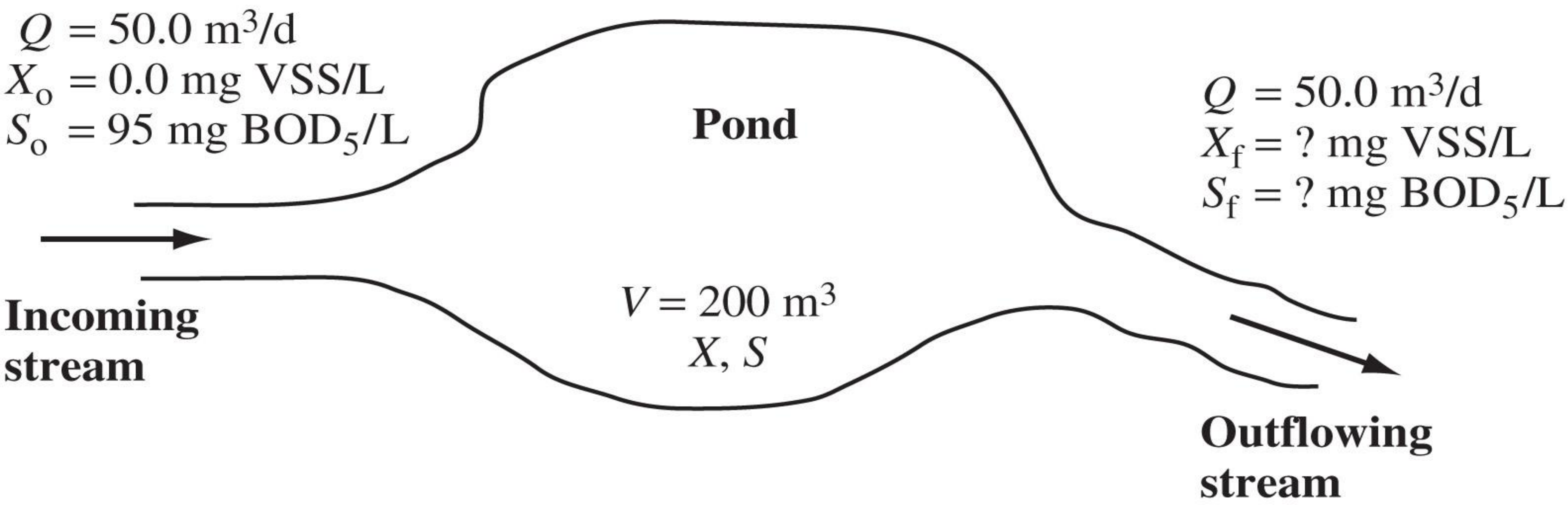
- First order as well:

$$r_d = \frac{dX}{dt} = -k_d X$$

- Thus Overall Growth Rate (r'$_g$):

$$r'_g = r_g + r_d = \frac{\mu_{\max} XS}{(K_s + S)} - k_d X$$

Example



- Assuming Monod kinetics (μ_{max} = 3 d^{-1}, k_d = 0.06 d^{-1}, K_s = 60 mg/L) what will be the effluent BOD concentration?

Example (solution)

Assume completely mixed, steady state

Mass balance on biomass:

$Q\,X_0 - Q\,X + V\,r'_g = 0$

As for chemostat example, $X_0 = 0$, Thus

$$0 = -QX + V\left(\frac{\mu_{\max} XS}{(K_s + S)} - k_d X\right)$$ and $V/Q = \theta = 200/50 = 4$ d, solving

$$S = \frac{K_s\left(1 + \theta k_d\right)}{\theta(\mu_{\max} - k_d) - 1}$$

$$S = \frac{60\left(1 + 4(0.06)\right)}{4(3 - 0.06) - 1} = 6.9 \text{ mg/L as BOD}_5$$

Microorganisms Involved in the Process

√ **Mixed culture, open, nonsterile systems**

- Bacteria (or archaea): The prime workers responsible for biodegradation of organics.
  Require soluble food. Solid food must be solubilized by exocellular enzymes.

- Algae: Important source of O_2 in lagoons and ponds (photosynthesis).
  Remove soluble N and P by uptake.

- Fungi can degrade many recalcitrant organics (e.g. cellulose) and grow under low pH (2), low N conditions. May be important in industrial waste treatment, composting.

- Protozoa and Rotifers: Consume solid food, including bacteria. Presence indicates well operating process (effluent polishers).

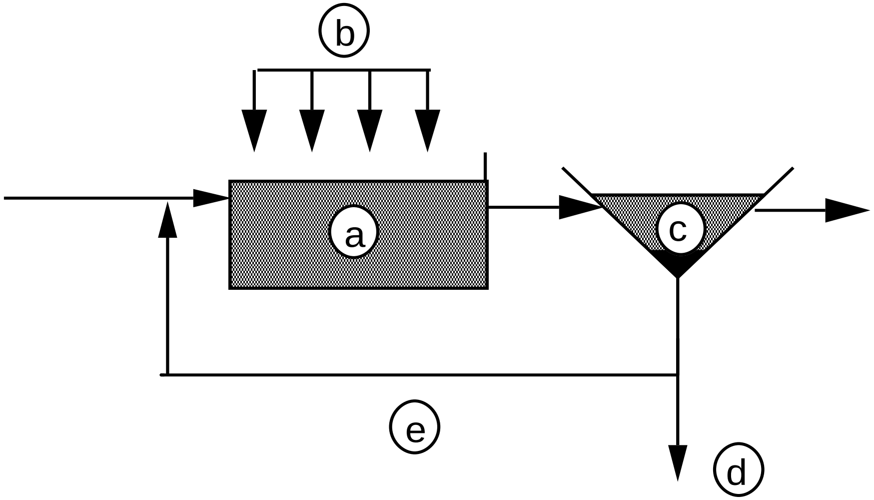
Types of Secondary Biological Reactors

- *Suspended Growth Processes:*
  - Activated Sludge
  - Aerated Lagoons (and Ponds)

- *Attached Growth Processes:*
  - Trickling Filters
  - Membrane Bioreactors (could be suspended growth processes, too)
  - Rotating Biological Contactors

Activated Sludge Process

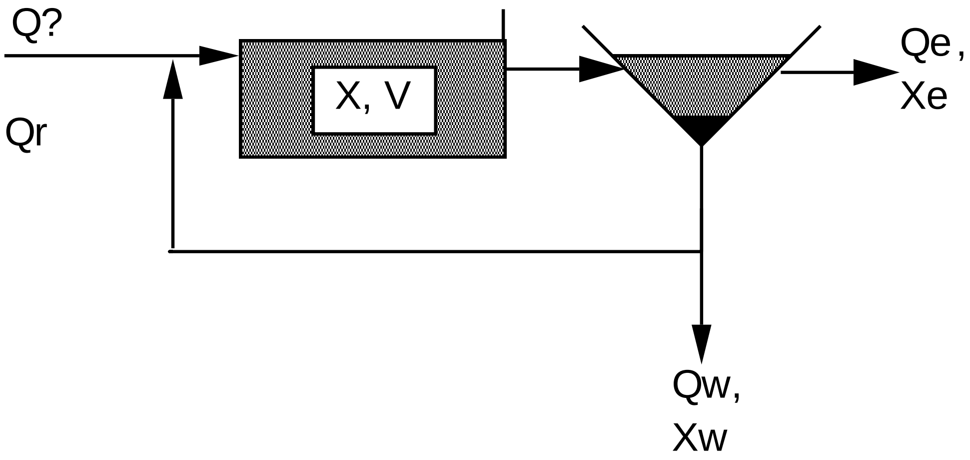
- Invented in 1914 (England)
- Popular and efficient biological treatment process
- Versatile & robust, most operation cost results from aeration.



a) **Aeration Tank:** Where bacteria grow and BOD is degraded (4-8 h)
b) **Aeration:** Supplies O_2 and mixing to keep bacteria in suspension
c) **Settling Tank:** Removes bacteria (MLSS) and clarifies effluent
d) **Wasting of Settled Sludge:** Controls cells residence time & conc.
e) **Recycle:** Returns activated bacteria to eat more waste

Activated Sludge Process

Activated Sludge Master Variables



1) θ_c = mean cell residence time (MCRT)

= solids retention time (SRT) = sludge age

= total mass in system/rate of mass leaving system

$$\theta_c = \frac{VX}{Q^e X^e + Q^w X^w} \approx \frac{VX}{Q^w X^w}$$

Thus, θ_c is controlled by wasting sludge (5 to 15 days typical)
(the less you waste, the larger θ_c, more contact time, higher efficiency)

Activated Sludge Master Variables

2) F/M (Food to Microorganisms Ratio)

$$F/M = \frac{\text{Waste concentration (BOD) fed per time}}{\text{Mass of bacteria present in system}} = \frac{Q^{o}\,(S^{o})}{VX}$$

Example:

Q° = Flow to aeration tank = 1 MGD

S° = Influent BOD_5 = 200 mg/l

X = 2,000 mg/l, V = 0.25 MG

What is F/M?

$$F/M = \frac{1\,(200)}{(0.25)\,2000} = 0.4\ day^{-1}$$

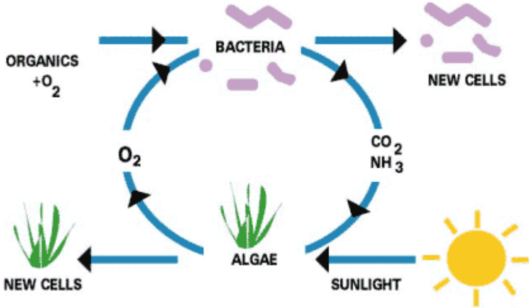
F/M = 0.4 lb BOD_5/lb MLVSS/day

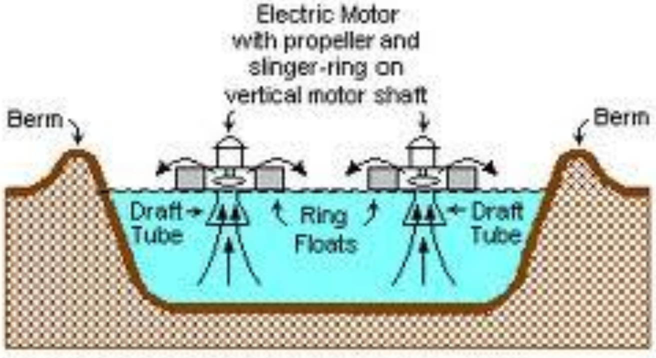
Typical F/M for Air-fed Activated Sludge = 0.1 to 0.5

Typical F/M for O_2-fed Activated Sludge = 0.2 to 2.4

Oxidation Ponds

- Suspended growth earthen basins, rural areas
- O_2 supplied by wind + algae (aerated lagoon has aerators)
- No recycle
- Good BOD removal (settling) and high coliform kill efficiency
- Small communities (<10,000) + industries (poultry, refineries)
- Shallow, large area requirement (A<10 acres avoids wind short-circuiting)



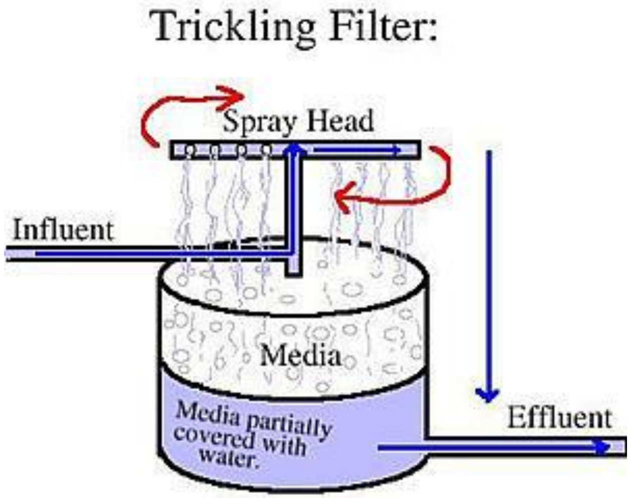


A TYPICAL SURFACE – AERATED BASIN

Note: The ring floats are tethered to posts on the berms.

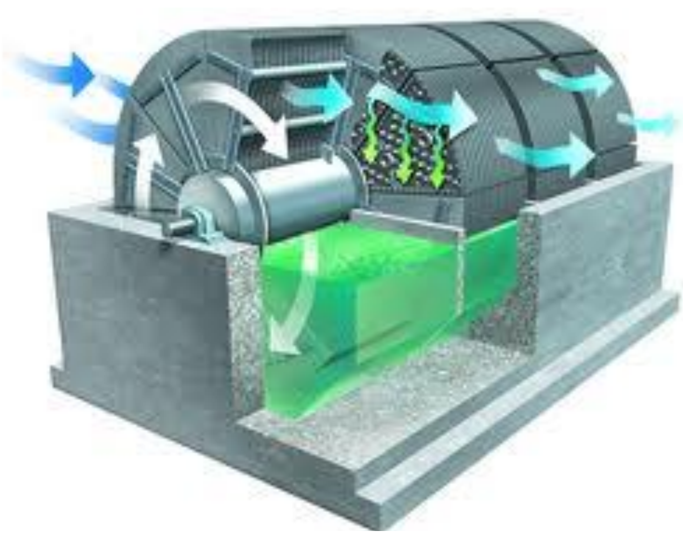
Trickling Filters

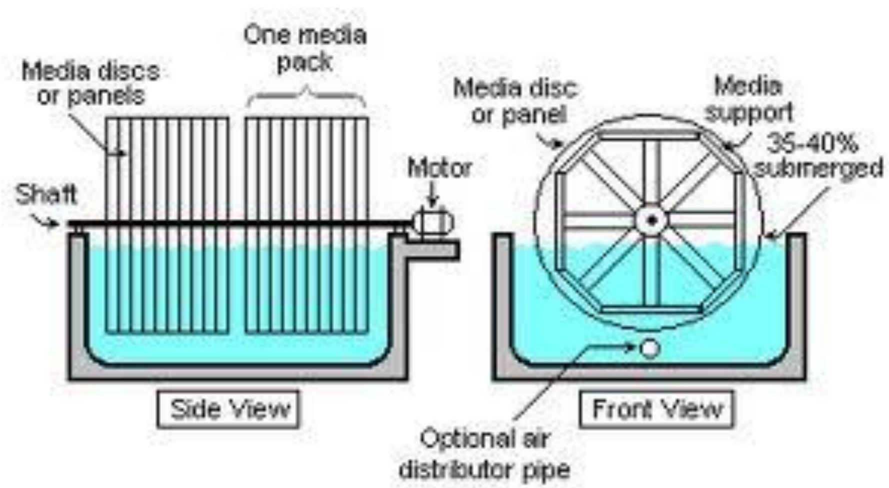
- Used since 1893. Waste is sprayed with a rotary sprayer, trickles down through filter medium (plastic or porous rocks)
- Air circulates in spaces and filter medium is covered by layer of slime - bacteria, fungi, algae (biofilm process)
- Waste diffuses into slime, where it is oxidized
- Treated wastewater may be recycled to wet the slime in the system and to dilute high-strength wastes and preclude oxygen flux limitation

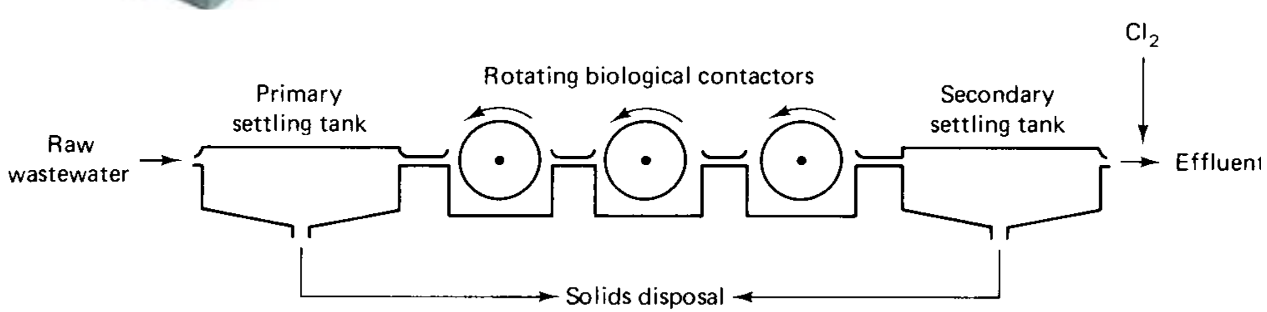


Rotating Biological Contactors (RBCs)

- Similar to trickling filter (i.e., also a biofilm process)
- Rather than pass wastewater over the media and slime, pass the media through the wastewater
- RBCs easier to use under varying flow conditions that TFs

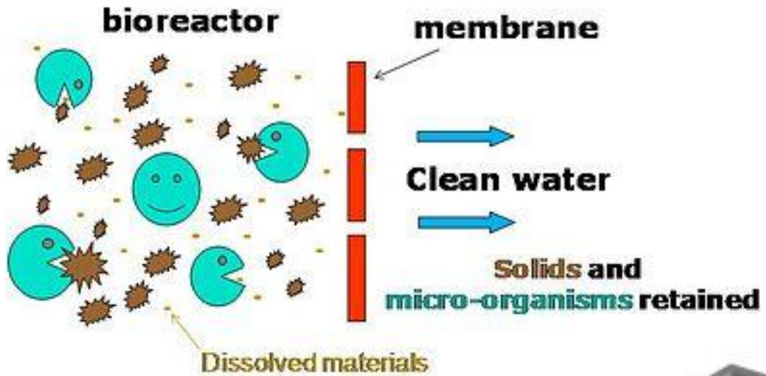




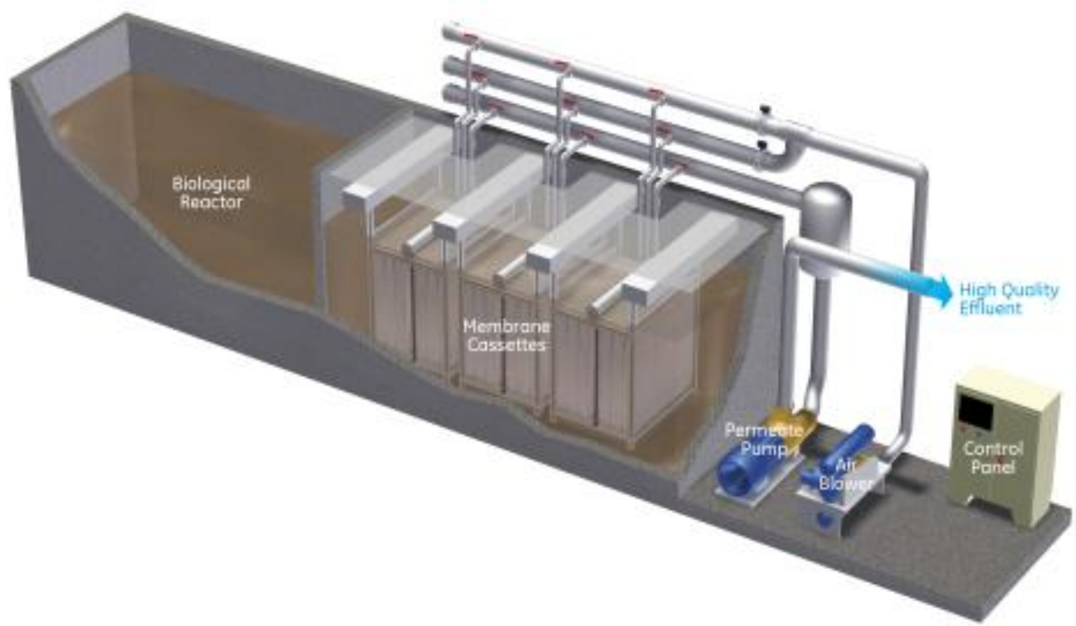


Membrane Bioreactor (MBR)

- High effluent quality that can be reclaimed for irrigation
- Small footprint (no need for clarifier) but energy intensive (high pressure is needed for filtration through membrane)



The membrane process replaces the clarifier to separate the cells



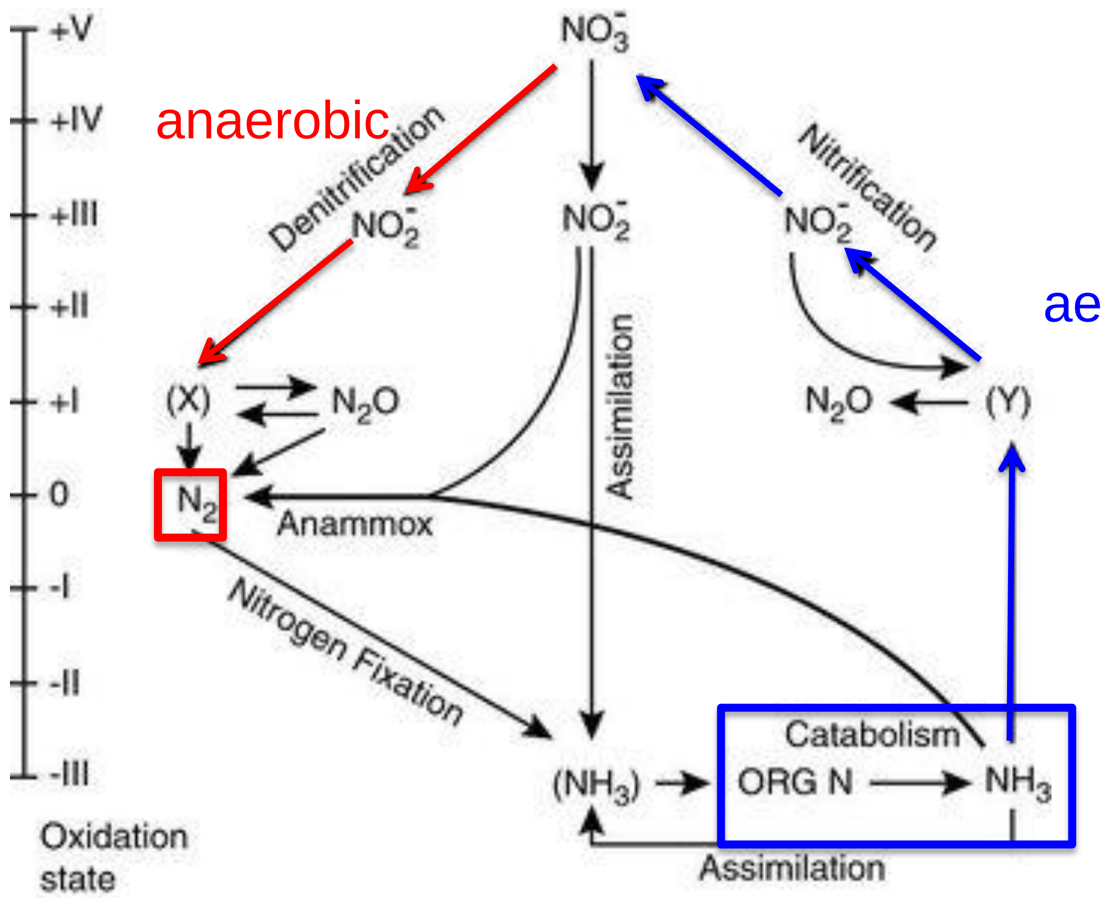
Nutrient (N, P) Removal

- Nitrogen (N) and Phosphorous (P) Removal is accomplished after the secondary treatment (tertiary treatment).
  - 70% of Nitrogen and Phosphorous usually remains after secondary treatment.
  - Main concern: Eutrophication of receiving water body.
- Removal can be integrated into the activated sludge or positioned in separate reactors past the secondary clarifier.

Nitrogen Removal

√ **Why?** NH_3 toxic to fish, NBOD, methamoglobinemia (NO_3^-), eutrophication.

Exploit the N cycle



Nitrification & Denitrification

- **Nitrification:** *Nitrosomonas* and *Nitrobacter* (aerobic, autotrophic bacteria) convert ammonium to nitrate (NO_3^-) in two steps:

  $NH_3 + CO_2 + 1.5\ O_2$ + *Nitrosomonas* $\rightarrow NO_2^- + H_2O + H^+$
  $NO_2^- + CO_2 + 0.5\ O_2$ + *Nitrobacter* $\rightarrow NO_3^-$

  Overall: $NH_4^+ + 2O_2 \rightarrow NO_3^- + 2H^+ + H_2O$
  Nitrospira "Comammox“ (COMplete AMMonia OXidiser) discovered, 2015

- **Denitrification:** Anaerobic, denitrifiers convert NO_3^- into N_2

  $NO_3^- \rightarrow NO_2^- \rightarrow NO + N_2O \rightarrow N_2$ (g)

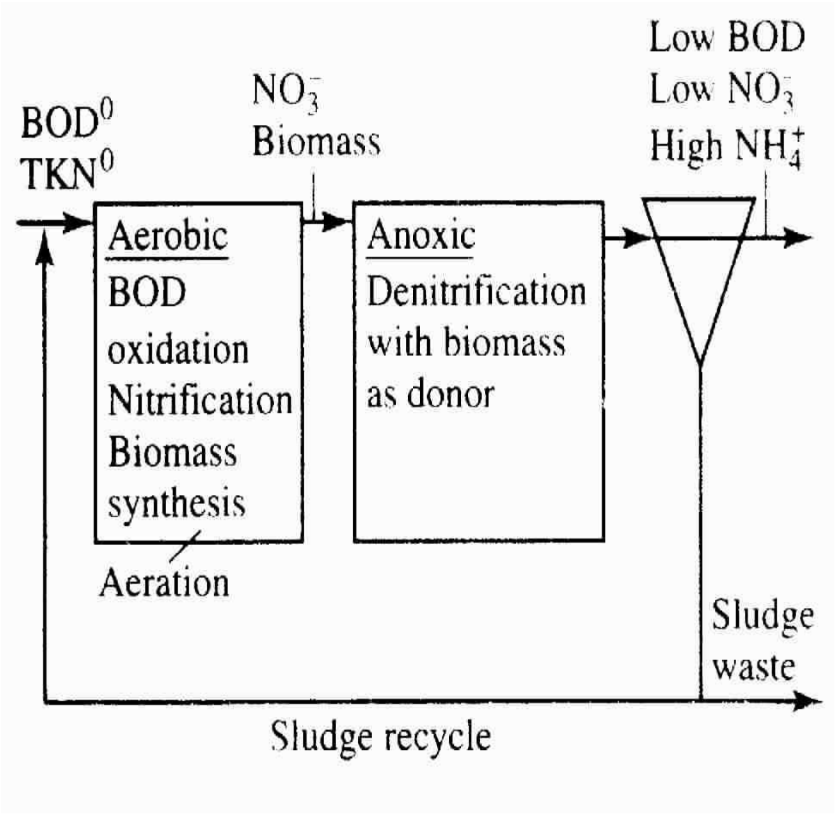
  $2NO_3^-$ + organic matter $\rightarrow N_2 + CO_2 + H_2O$

  Nitrate and Nitrite are used as electron acceptors by heterotrophic bacteria\ (e.g., *Paracoccus denitrificans)*

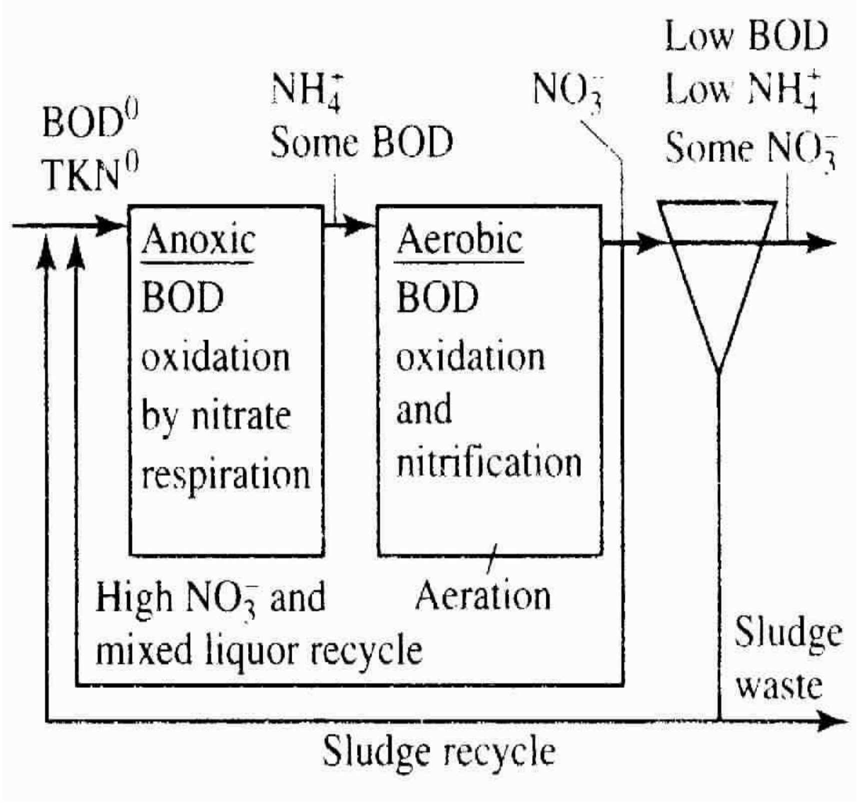
  Organic matter may need to be added to the system or in tandem with activated sludge (recycled wastewater, acetate, methanol, etc.)

Nitrification & Denitrification

- **Post-denitrification:**



- **Pre-denitrification**



Biological Phosphorus Removal

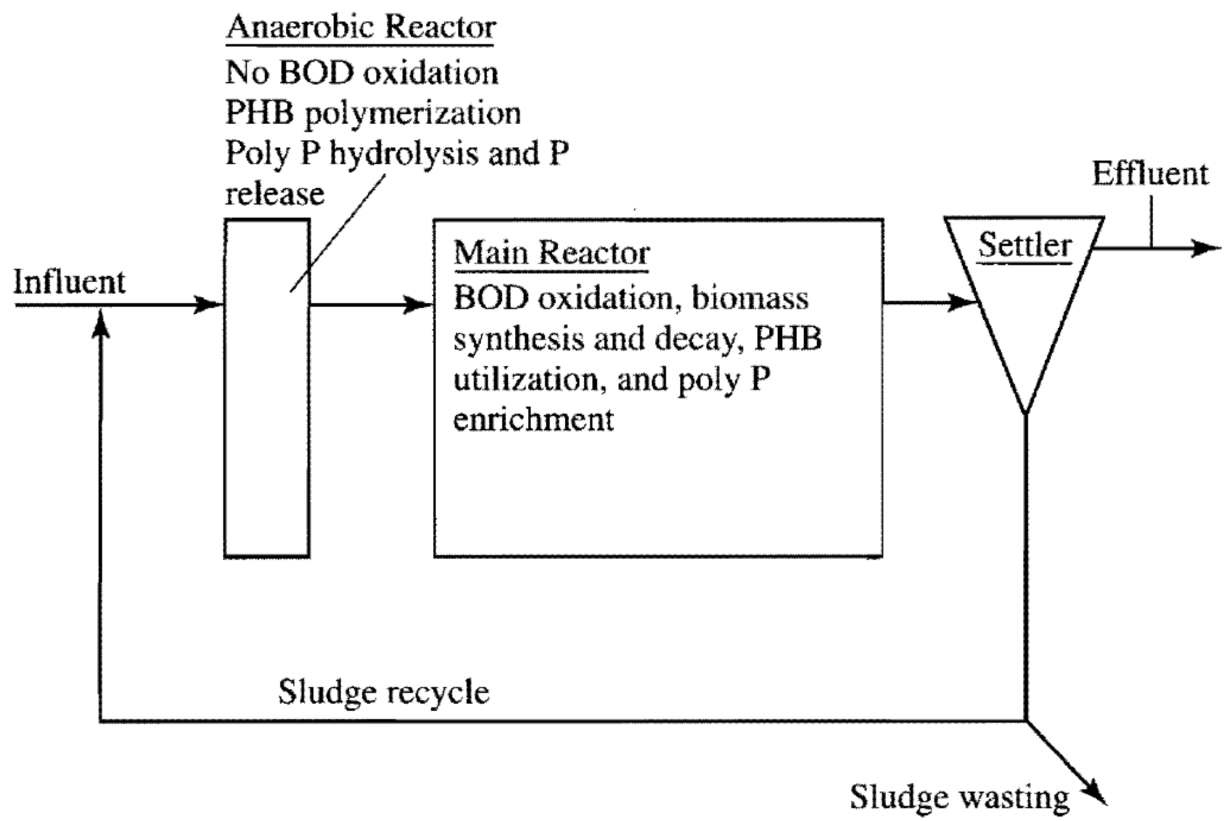
√ Enhanced Biological Phosphorus Removal (EBPR)

- 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.

Biological Phosphorus Removal

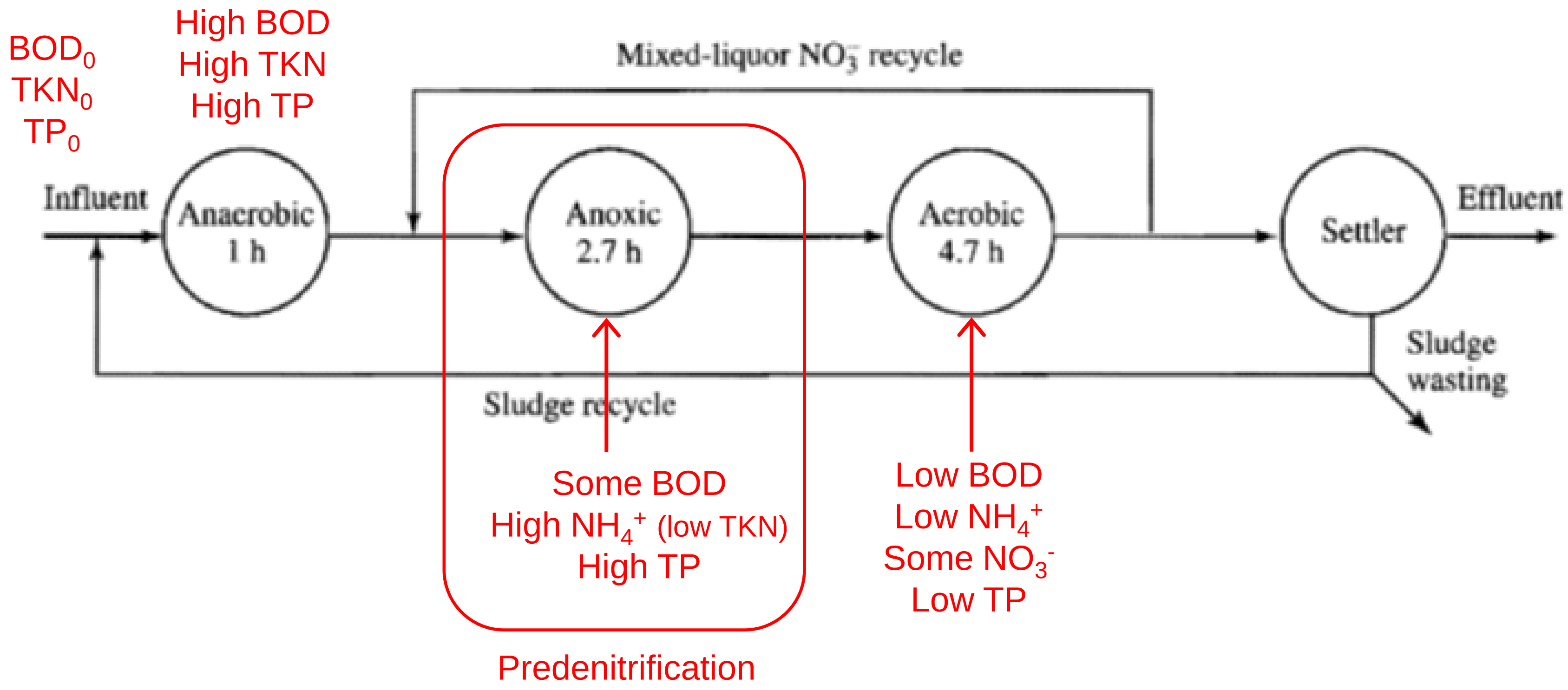


Schematic of the required components of an activated sludge process active for enhanced biological phosphorus removal.

Biological Phosphorus Removal

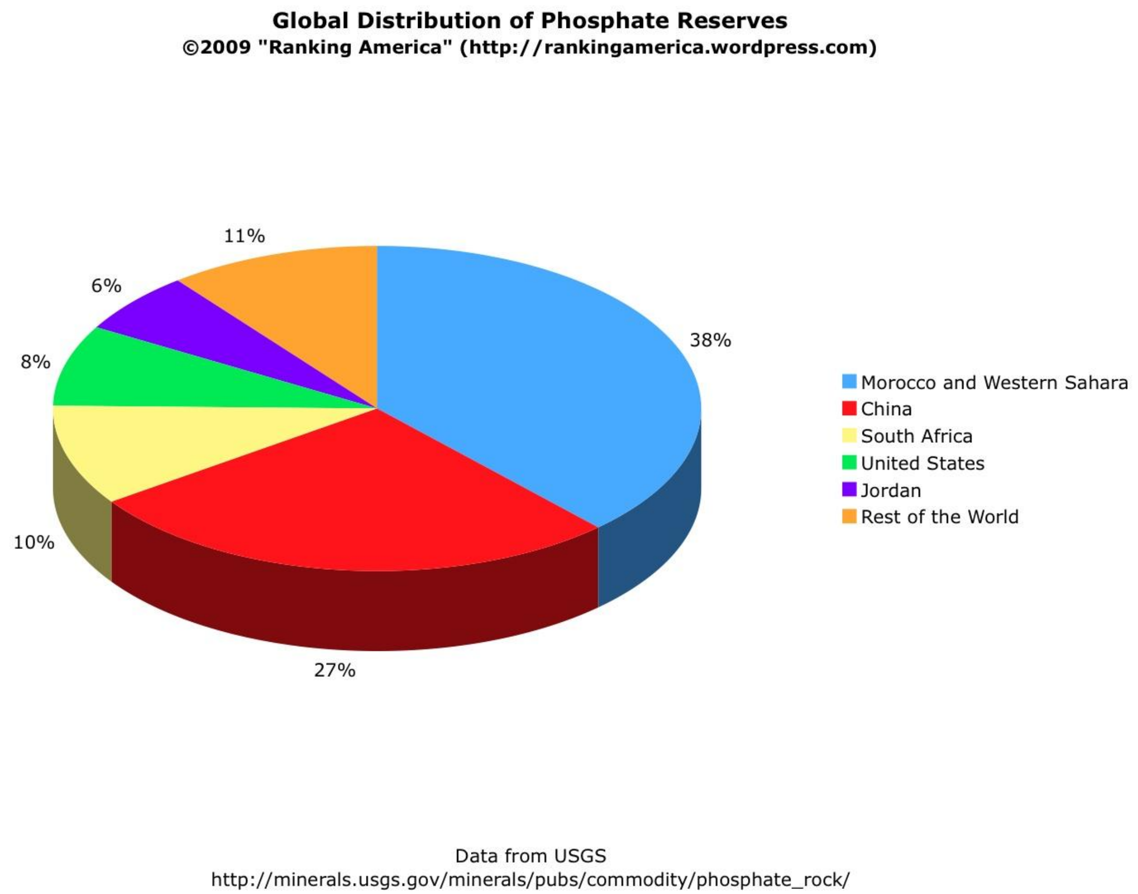
- **A2O (Anaerobic/Anoxic/Aerobic) process**

Combined processes with carbon and nitrogen removal



Importance of Phosphorus Recovery

- The known reserves of currently exploitable phosphate rock are estimated at about 40 billion tons. At the peak rate of consumption (150 million tons per year, mainly as fertilizer) these reserves will not last over 250 years.



Anaerobic Sludge Digestion