# C9 1B

# Lecture 4: Wastewater biological treatment: Basic concepts and principles

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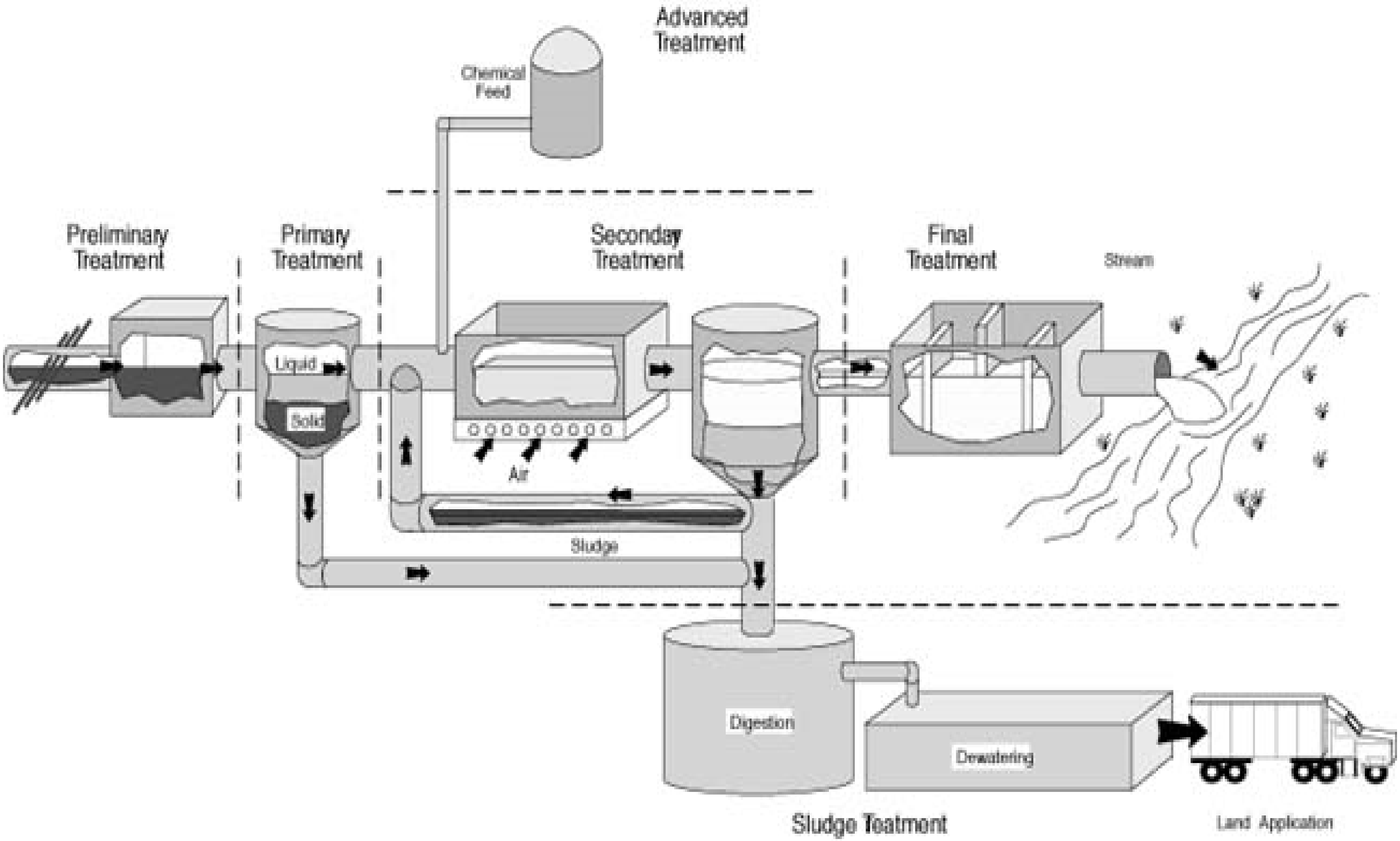
# Outline

- Overview of secondary treatment
- Overview of biological treatment
- Basic kinetics of biological growth
- Industrial example

# General Wastewater Treatment Process



# Overview of secondary treatment

- The major purpose is to

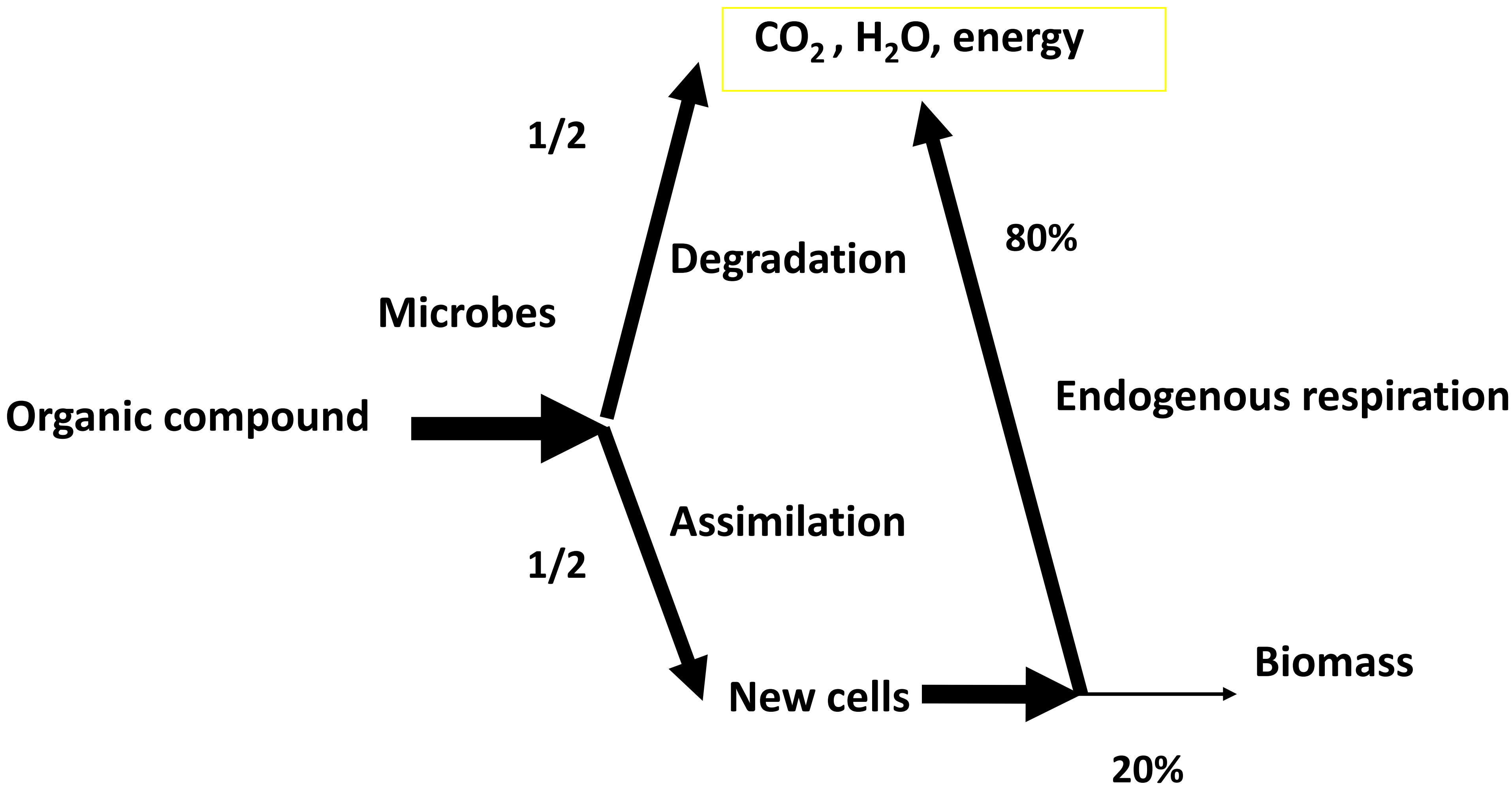
  - remove the soluble BOD that escapes primary treatment;

  - provide further removal of suspended solids.

- Biological treatment is a key:

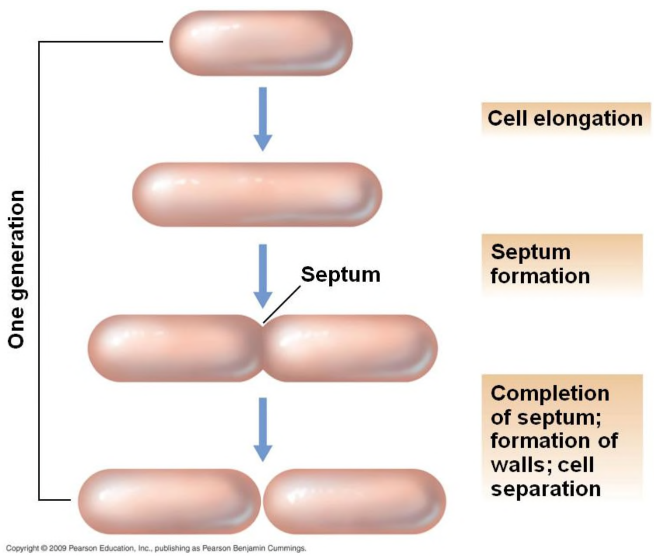
  - microbes in wastewater can decompose organic compounds (contributing to BOD) naturally. biological treatment is an enhanced natural self-purification;

# Microorganisms metabolism



# Growth of Bacterial populations

- **Exponential growth** : the number of cells doubles during a constant time interval - increase exponentially.
- **Result:** explosive increase in cell numbers from initially very small cell numbers.




Binary fission

| Time (h) | Total number of cells | Time (h) | Total number of cells |
|---|---|---|---|
| 0 | 1 | 4 | 256 ($2^8$) |
| 0.5 | 2 | 4.5 | 512 ($2^9$) |
| 1 | 4 | 5 | 1,024 ($2^{10}$) |
| 1.5 | 8 | 5.5 | 2,048 ($2^{11}$) |
| 2 | 16 | 6 | 4,096 ($2^{12}$) |
| 2.5 | 32 | . | . |
| 3 | 64 | . | . |
| 3.5 | 128 | 10 | 1,048,576 ($2^{19}$) |

Figure 6-6a Brock Biology of Microorganisms 11/e

# Growth measurement

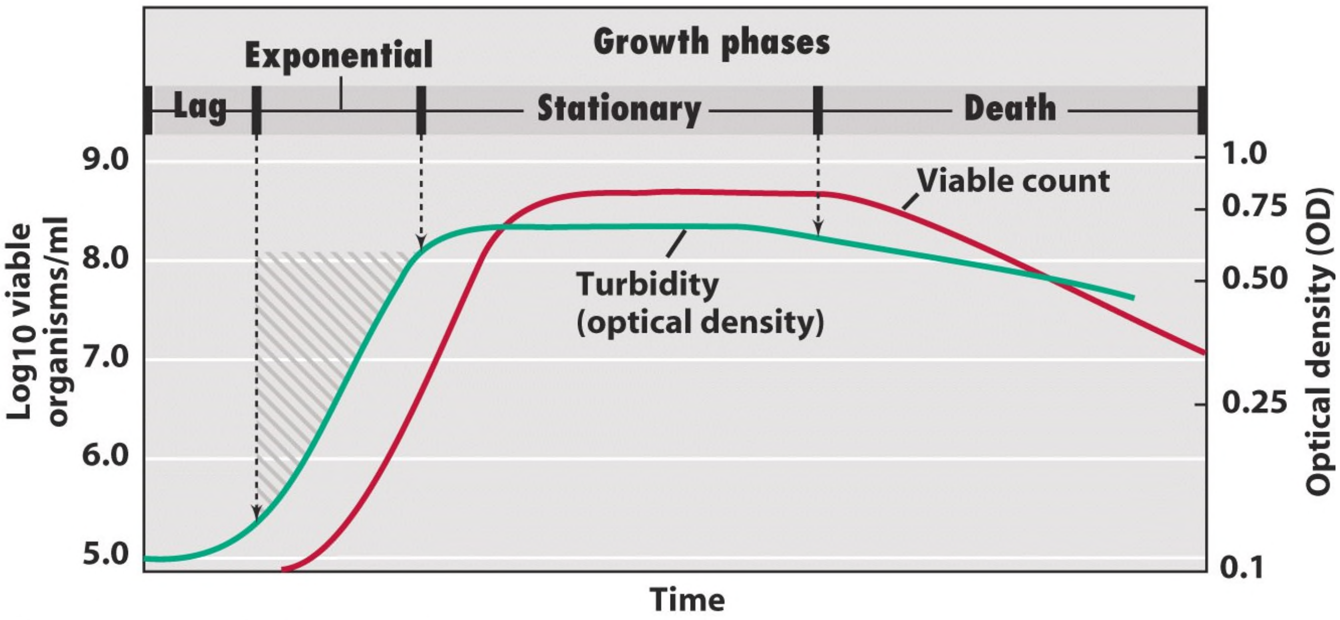
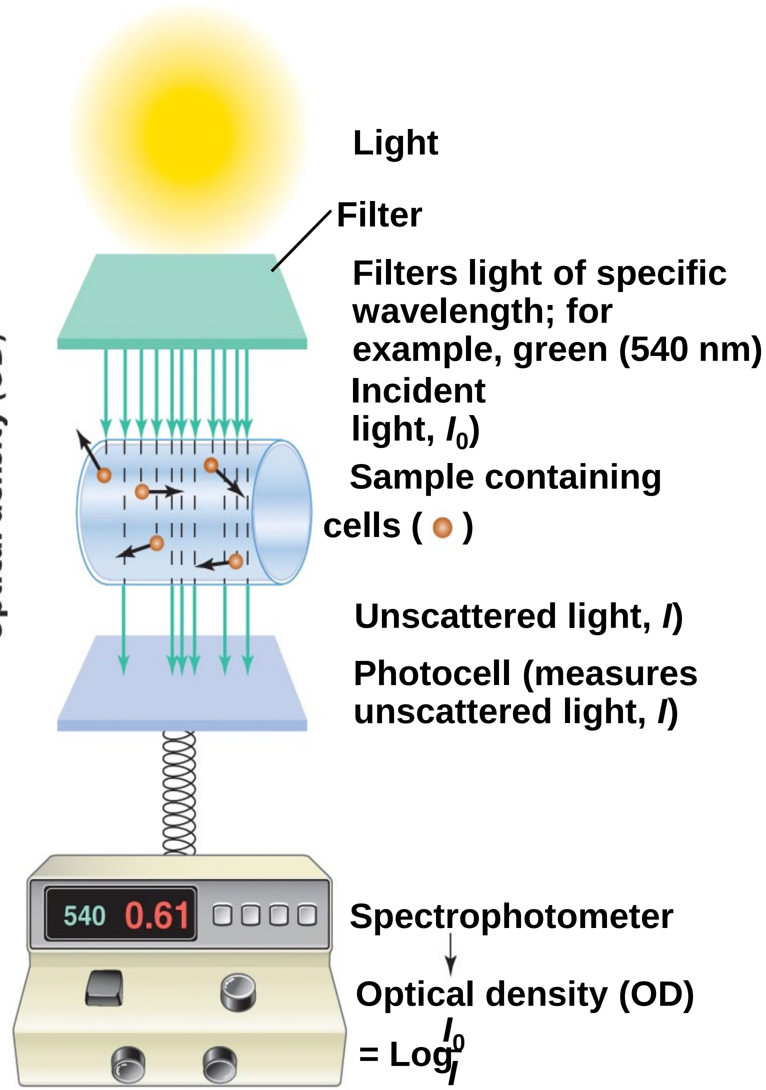
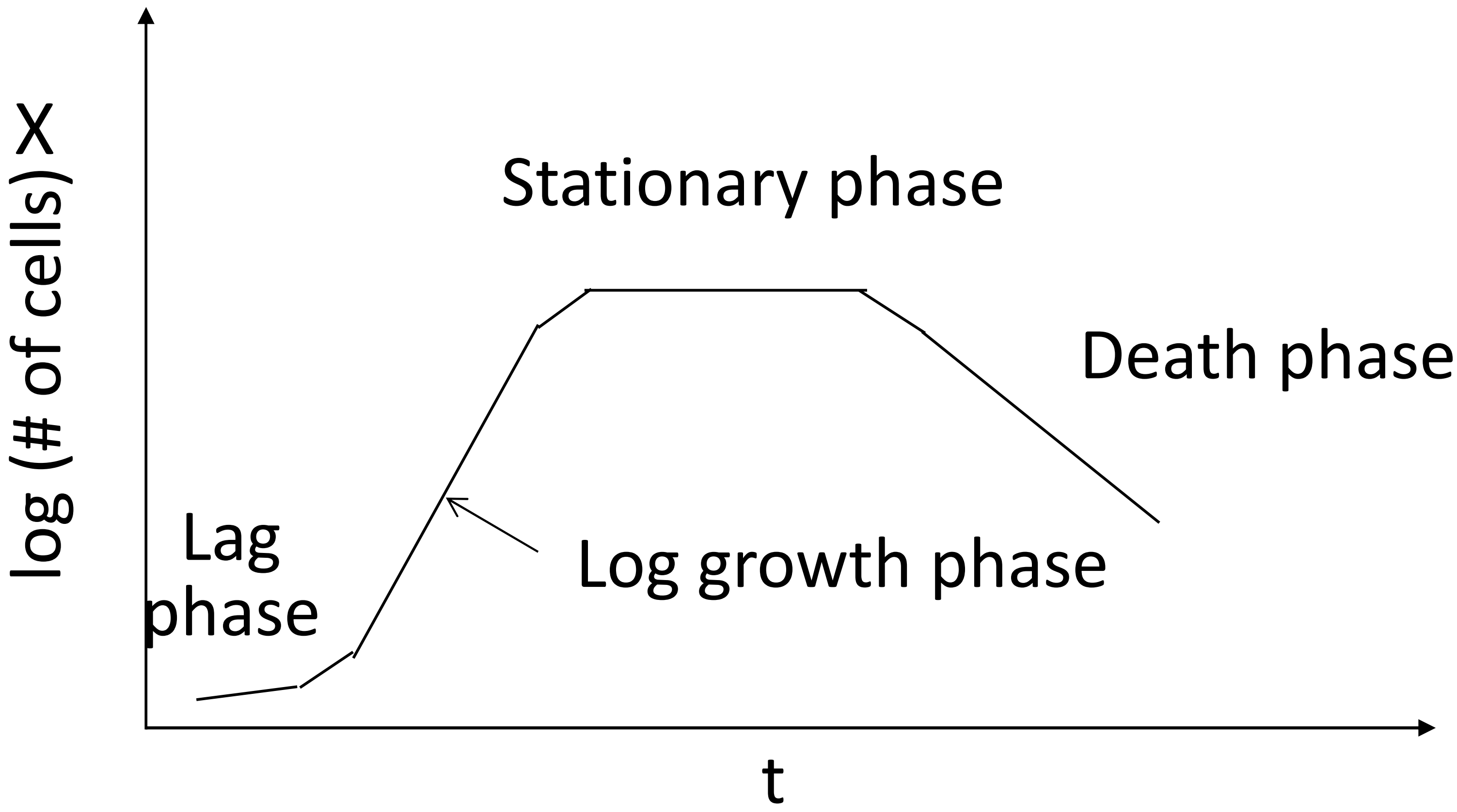



Figure 6-8 Brock Biology of Microorganisms 11/e


(a)

# Basic Kinetics of Biological Growth




In the log growth phase, the growth rate of biomass increase is

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

$\mu$ = special growth rate, $t^{-1}$, $X$ = concentration of biomass, mg/L.

$r_g$ = rate of bacterial growth (mass/unit volume · time, e.g. mg/L ·h)

# Calculating growth rate during exponential growth

$dX/dt = \mu X$ where $\mu$ = specific growth rate ($h^{-1}$)

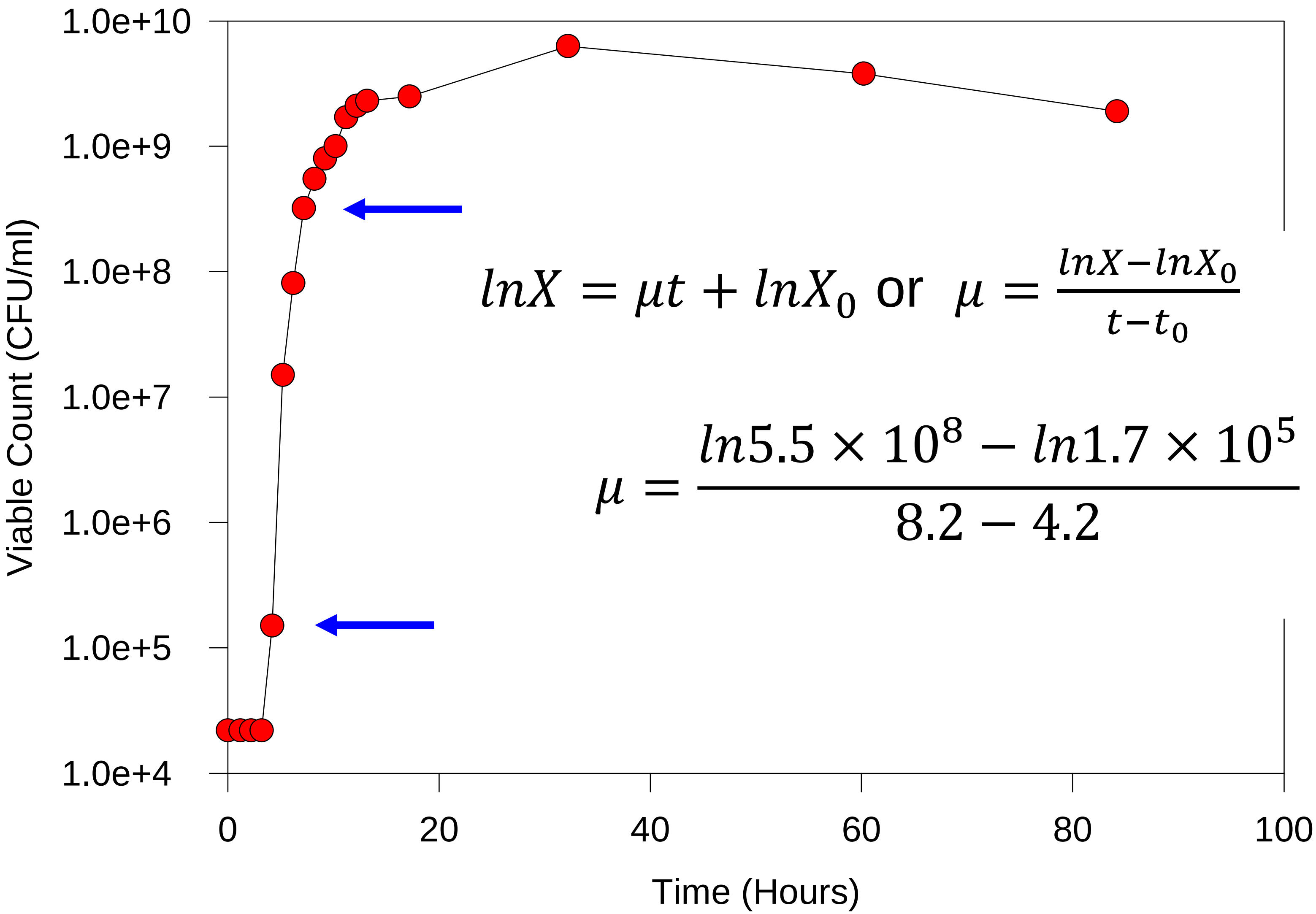
Rearrange: $dX/X = \mu dt$

Integrate: $lnX = \mu t + C$, where $C = lnX_0$

$$lnX = \mu t + lnX_0 \quad or \quad X = X_0 e^{\mu t}$$

Note that μ, the growth rate, is the slope of this straight line

# Find the slope of this growth curve




$$lnX = \mu t + lnX_0 \text{ or } \mu = \frac{lnX - lnX_0}{t - t_0}$$

$$\mu = \frac{ln5.5 \times 10^8 - ln1.7 \times 10^5}{8.2 - 4.2} = 2h^{-1}$$

# Basic Kinetics of Biological Growth

- Monod developed a model that assumes the biomass growth rate is limited by the rate of enzyme reactions involving the limiting food or substrate compound. The Monod equation is

$$\mu = \frac{\mu_m S}{K_s + S}$$

Where

$\mu$ = special growth rate, $t^{-1}$

$\mu_m$ = the maximum special growth rate constant $t^{-1}$,

$S$ = concentrations of the limiting food in solution, mg/L,

$Ks$ = half saturation constant, mg/L (or concentration of limiting food when $\mu = 0.5\ \mu_m$ ).

$$r_g = \frac{dX}{dt} = \mu X = \frac{\mu_m S X}{K_s + S}$$

# Endogenous Decay

- Consider the microbial natural decay;
- Assumption: decrease in cell mass is proportional to conc. of organisms (cell mass) present (first order).

$$r_d = (\frac{dX}{dt})_{endog.decay} = -k_d X$$

$k_d$ = endogenous decay rate constant, $t^{-1}$

- So the net growth rate $r_g$' is

$$r_g' = r_g + r_d$$

$$(\frac{dX}{dt})_{net\_growth} = (\frac{dX}{dt})_{biomass\_produced} + (\frac{dX}{dt})_{endog.\_decay}$$

$$(\frac{dX}{dt})_{net\_growth} = \mu X - k_d X = \frac{\mu_m S X}{K_s + S} - k_d X$$

# Food (BOD or COD) utilization

- Food (BOD or COD): converted to new cells oxidized to inorganic and organic end product
- Only a part of the food is converted to the biomass

$$r_g = -Yr_{su} \qquad r_{su} = \frac{dS}{dt} = -\frac{1}{Y} r_g$$

$$\frac{dS}{dt} = -\frac{1}{Y}\left(\frac{dX}{dt}\right)_{biomass\_produced} = -\frac{1}{Y}\frac{\mu_m SX}{K_s + S}$$

$Y$ = yield coefficient,

mass biomass produced/ mass substrate (food, BOD, COD) utilized

$r_{su}$ = substrate utilization rate (mass/unit volume · time)

$r_g$ = rate of bacterial growth (mass/unit volume · time)

# Summary of key equations

- Monod equation

$$\mu = \frac{\mu_m S}{K_s + S}$$

- Net growth rate of biomass

$$r'_g = (\frac{dX}{dt})_{net\_growth} = \mu X - k_d X = \frac{\mu_m SX}{K_s + S} - k_d X$$

- Food (BOD or COD) utilization rate

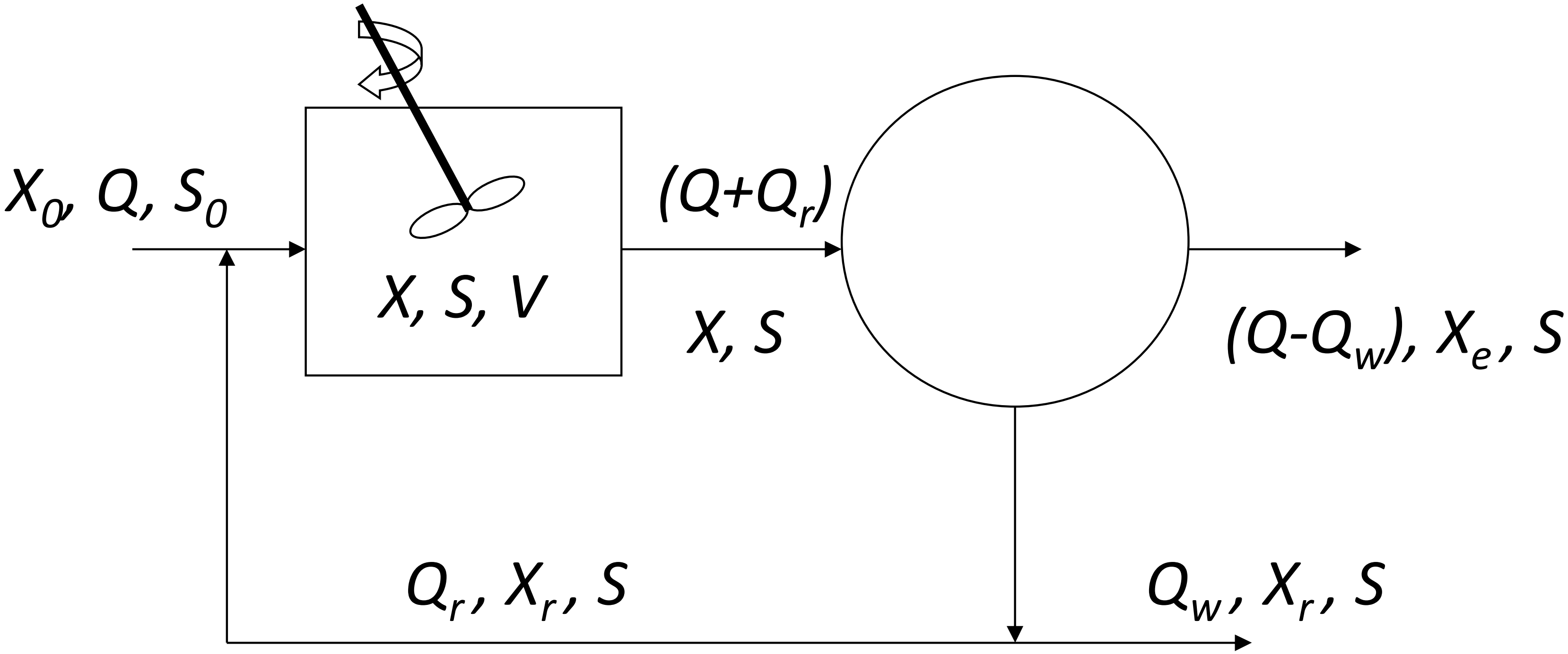
$$r_{su} = \frac{dS}{dt} = -\frac{1}{Y}(\frac{dX}{dt})_{biomass\_produced} = -\frac{1}{Y}\frac{\mu_m SX}{K_s + S}$$

# Types of Aeration systems


- Diffused air system
- Mechanical aeration system

**Aeration tank**

# Completely mixed activated sludge process




$Q$: flow rate, $m^3/d$;

Qw: flow rate of liquid containing biomass to be wasted, $m^3/d$;

Qr: flow rate of returned sludge, $m^3/d$;

$X_0$: biomass concentration (VSS) entering aeration tank, mg/L;

$X$: biomass concentration (MLVSS), mg/L;

*Xe:* biomass concentration (VSS) in effluent from secondary settling tank, mg/L;

Xr: biomass concentration (VSS) returned to aeration tank, mg/L;

$S_0$: substrate concentration entering aeration tank, $BOD_5$, mg/L;

*S:* substrate concentration in aeration tank and effluent, $BOD_5$, mg/L.

# Sludge Retention Time (sludge age) $\theta_c$

$\theta_c$ is the average time the activated-sludge solids stay in the system. $\theta_c$ is also called Sludge Age.

- If the sludge is not able to reproduce itself before being washed out if the system, failure will result;
- Higher sludge ages cause the sludge to undergo more endogenous decay;

$\theta_c$ is expressed as the average amount of time the sludge spends in the aeration basin.

$$\theta_c = \frac{\text{Mass of solids in the aeration tank } (VX)}{\text{Solids removal rate from the system } (Q_w X_r + (Q-Q_w)X_e)}$$

$$= \frac{VX}{Q_w X_r + (Q-Q_w)X_e}$$

# Substrate Balance

In – Out + Reaction = Accumulation

$QS_0$ $\quad QS$ $\quad Vr_{su}$ $\quad V\frac{dS}{dt}$

At the steady state, $\frac{dS}{dt} = 0$

$$QS_0 - QS + Vr_{su} = 0$$

$$r_{su} = -\frac{Q(S_0 - S)}{V} = -\frac{S_0 - S}{V/Q} \qquad \text{Eq. (4)}$$

# Biomass Balance

In – Out + Reaction = Accumulation

$$QX_0 \qquad Q_w X_r \qquad (Q - Q_w)X_e \qquad r_g{}'V \qquad V\frac{dX}{dt}$$

$$QX_i - Q_w X_r - (Q - Q_w)X_e + r_g{}'V = V\frac{dX}{dt}$$

✓the steady state $\frac{dX}{dt} = 0$

✓ Assume influent biomass is negligible compared to other biomass, $X_i = 0$

$$Q_w X_r + (Q - Q_w)X_e = Vr_g{}' = V\left(\frac{\mu_m SX}{K_s + S} - k_d X\right) \qquad \text{Eq. (5)}$$

# Determine the effluent S

$$Q_w X_r + (Q - Q_w) X_e = V r_g^{'} = V[(\mu_m \frac{SX}{S + K_s}) - k_d X)] \quad \text{Eq. (5)}$$

$$\theta_c = \frac{VX}{Q_w X_r + (Q - Q_w)(X_e)}$$

$\longleftarrow$ Mass of solids in the aeration tank

$\longleftarrow$ Solids removal rate from the system

Substituting $\theta_c$ to Eq. (5) and solving S,

$$S = \frac{K_s (1 + k_d \theta_c)}{\theta_c (\mu_m - k_d) - 1} \quad \text{Eq. (6)}$$

- S is soluble BOD (BOD5) or COD, not the total BOD or COD.
- **Once $\theta_c$ is selected, the concentration of BOD5 in effluent is fixed.**

# Food to Microorganism ($F/M$) Ratio

The F/M ratio (sludge loading) expresses the potential food availability to the microbial populations.$_{\tau}$

$$F/M = \frac{QS_0}{VX} = \frac{\text{Total applied substrate rate}}{\text{Total microbial biomass}}$$

$$= \frac{S_0}{X\frac{V}{Q}} = \frac{S_0}{Xt_R}$$

$$t_R = \frac{V}{Q}$$

$t_R$ = the hydraulic retention time (HRT), T

The sludge retention time $\theta_c$, can be given by

$$\theta_c = \frac{VX}{Q_w X_r + (Q - Q_w) X_e} = \frac{VX}{V r_g'} = \frac{X}{r_g'} = \frac{X}{-Y r_{su} - k_d X}$$

$$\frac{1}{\theta_c} = \frac{-Y r_{su} - k_d X}{X} = -Y \frac{r_{su}}{X} - k_d$$

The term $-r_{su}/X$ is known as specific substrate utilisation rate, *U*.

Recall Eq(4)

$$r_{su} = -\frac{S_0 - S}{t_R}$$

$$U = -\frac{r_{su}}{X} = \frac{Q(S_0 - S)}{VX}$$

Eq. (7)

$$\boxed{\frac{1}{\theta_c} = \frac{Y(S_0 - S\ )}{t_R X} - k_d = YU - k_d}$$

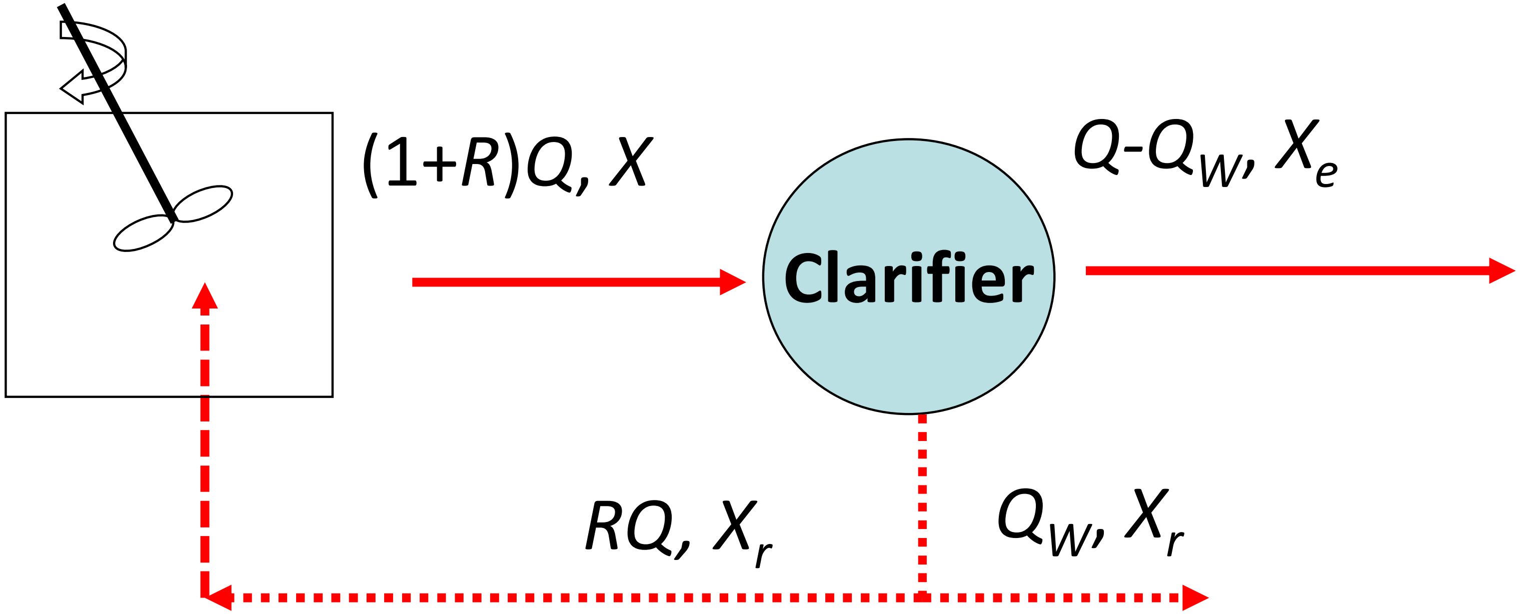
Eq. (8)

# Determine the concentration of biomass X in aeration tank

The biomass concentration X in the reactor can be obtained by substituting Eq. (7) into Eq. (8) and solving for biomass concentration X

$$X = \frac{\theta_c (Y)(S_0 - S)}{t_R (1 + k_d \theta_c)} \qquad \text{Eq. (9)}$$

# Determine the rate of sludge recycle, R




Consider mass balance for biomass in secondary clarifer only

$$Q(1+R)X = (Q - Q_w)X_e + RQX_r + Q_w X_r$$

# The rate of sludge recycle R

$$R = \frac{1 - \frac{t_R}{\theta_c}}{\frac{X_r}{X} - 1}$$

It is from the biomass balance equation of the whole system.

$\theta_c$ is the sludge retention time, or sludge age
$t_R$ is hydraulic retention time

# Sludge production rate

The net activated sludge production rate is determined by

$$P_x = Y_{obs}Q(S_0 - S)$$

$P_x$ = net waste activated sludge produced each day in terms of VSS, kg/d
$Y_{obs}$ = observed yield, kg MLVSS/kg BOD5 removed. It is determined by experiments.

# Oxygen requirement

$C_5H_7NO_2 + 5O_2 \rightarrow 5CO_2 + 2H_2O + NH_3$ + energy for cells

$$\frac{Oxygen}{Cells} = \frac{5(32)}{113} = 1.42$$

Oxygen required (kg $O_2$/day)= BOD removed – BOD in waste sludge

$$M_{O2} = \frac{Q(S_0 - S)}{f} - 1.42P$$

- f is conversion factor for converting substrate to BOD, usually f=1.
- $1.42P_x$ is subtracted because it represents the portion of substrate that gets converted to biomass and then removed from system before it exerts its oxygen demand.

# Equation summary I

Key equations of completed mixed activated sludge process

$t_R$ = the hydraulic retention time

$$t_R = \frac{V}{Q} = \frac{S_0 - S}{UX}$$

$\theta_c$= Sludge age
(the sludge retention time)

$$\frac{1}{\theta_c} = \frac{Y(S_0 - S\ )}{t_R X} - k_d = YU - k_d$$

$P_x$ = activated sludge production rate

$$P_x = Y_{obs} Q(S_0 - S)$$

$M_{o2}$ = oxygen requirement

$$M_{O2} = \frac{Q(S_0 - S)}{f} - 1.42P$$

# Equation summary II

Key equations of completed mixed activated sludge process

Effluent S, soluble BOD5 in aeration tank and effluent (mg/L)

$$S = \frac{K_s(1+k_d\theta_c)}{\theta_c(\mu_m - k_d) - 1}$$

Biomass in aeration tank (mg/L)

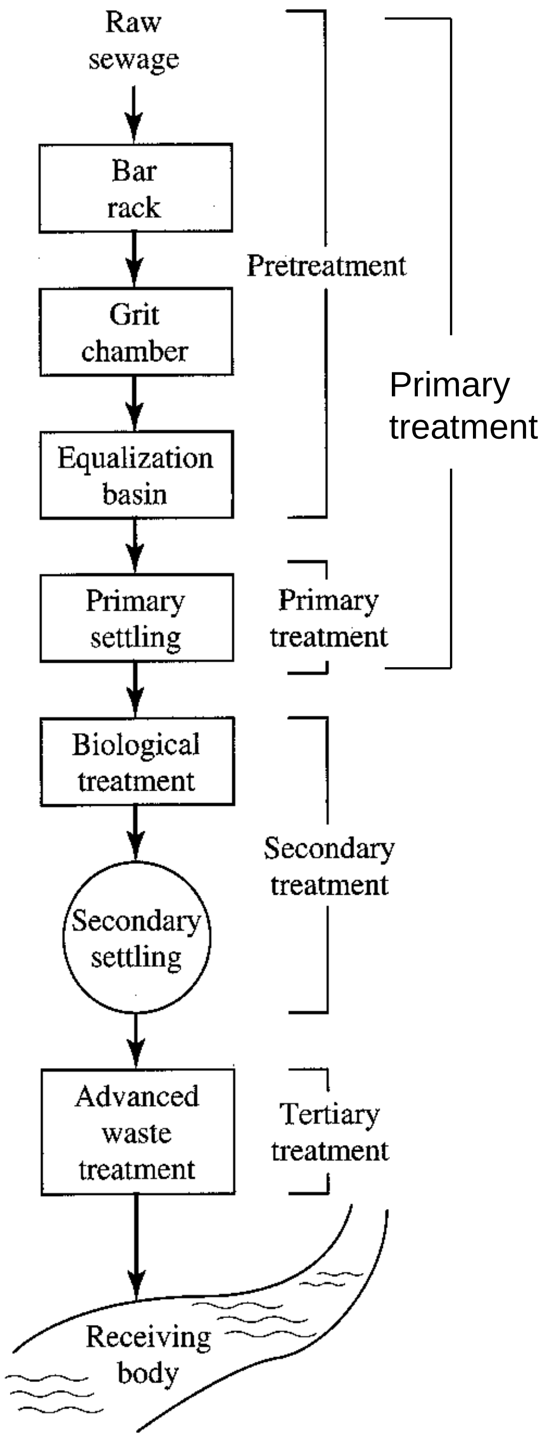
$$X = \frac{\theta_c(Y)(S_0 - S)}{t_R(1+k_d\theta_c)}$$

Food : microbes ratio

$$F/M = \frac{QS_0}{VX}$$

The rate of sludge recycle

$$R = \frac{1 - \frac{t_R}{\theta_c}}{\frac{X_r}{X} - 1}$$




# Municipal Wastewater Treatment Systems

- Pretreatment – removes materials that can cause operational problems, equalization optional
- Primary treatment – remove ~60% of solids and ~35% of BOD
- Secondary treatment – remove ~85% of BOD and solids
- Tertiary treatment – varies: 95+ % of BOD and solids, N, P

# Use an industrial case to understand N and P removal

# Coke pushing

# Main components of coke oven wastewater

- Ammonia – typically 5 - 10 g/l
- Phenols 200 - 650 mg/l
- Thiocyanate $(SCN^-)$200 - 400 mg/l
- Chemical oxygen demand 1000 - 4500 mg/l
- Tar 35 – 45 kg/tonne coke produced

# Energy in Tata wastewater

What is potential energy benefit of maximum energy recover using Tata wastewater?

Given that energy content= 15 kJ/g-COD.

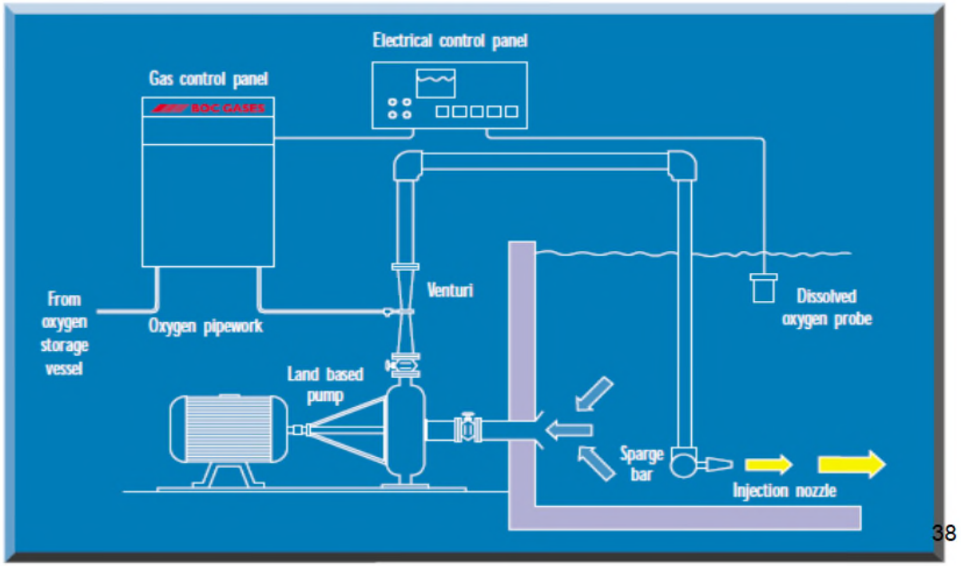
- Scunthorpe BET plant: Flow rate = 2100 $m^3$ /day, COD= 950 mg / L
- Port Talbot BET plant: Flow rate = 2300 $m^3$ /day, COD = 1600 mg /L

It is equivalent to 3600 L ethanol/day in terms of energy content.

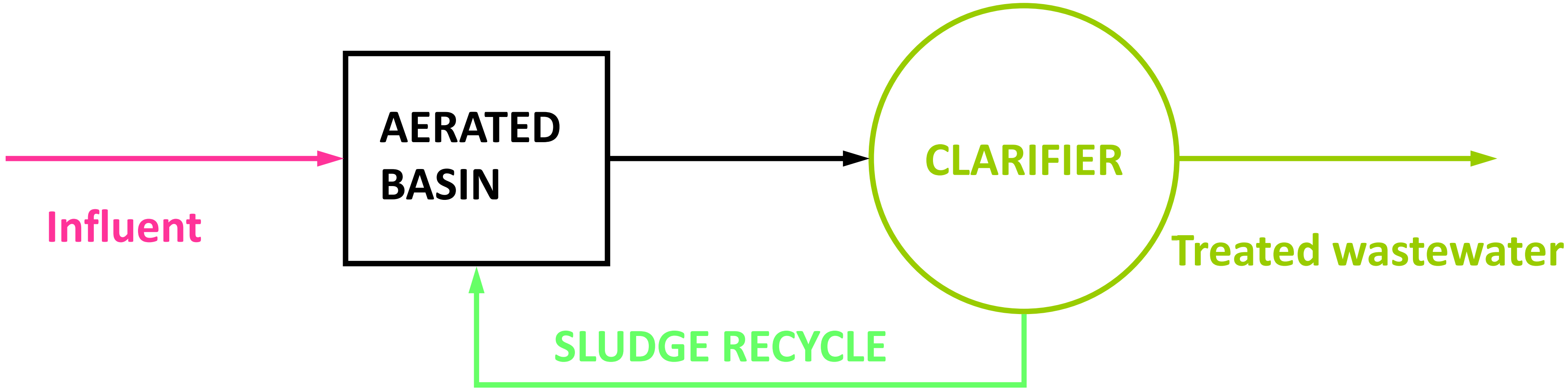
If energy transfer efficiency is 30%, 1080 L ethanol/day can be recovered.

# Pure oxygen aeration

- Injection of pure oxygen



# Single stage activated sludge process




| | |
|---|---|
| **Main reaction** | **Oxidation of COD (e.g. phenols) and thiocyanate** |

# Nitrogen Removal

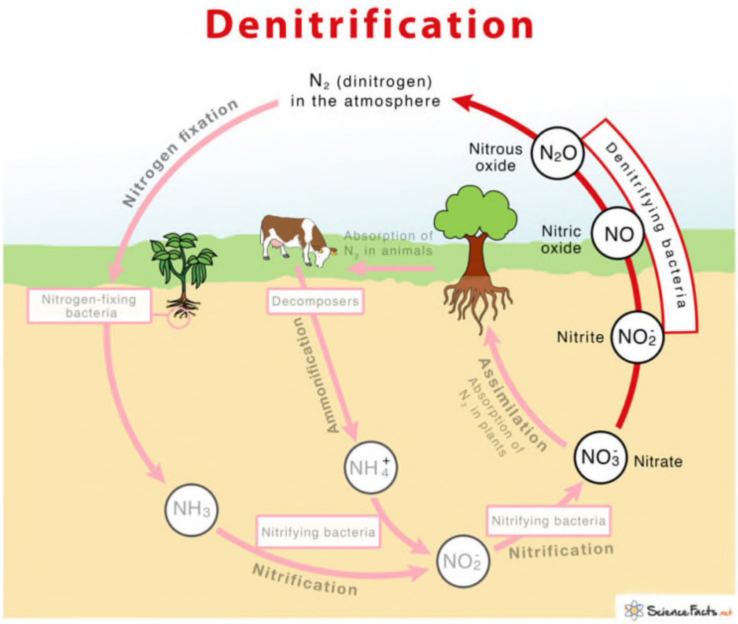
- Forms: $NH_3$, $NH_4^+$, $NO_2^-$, $NO_3^-$
- Nitrification/ De-nitrification
  - Occurs
    - in activated sludge process - by increasing the detention time in activated sludge basin
    - in separate reactor
  - Nitrification

    Nitrifier - autotrophic bacteria, slow grower

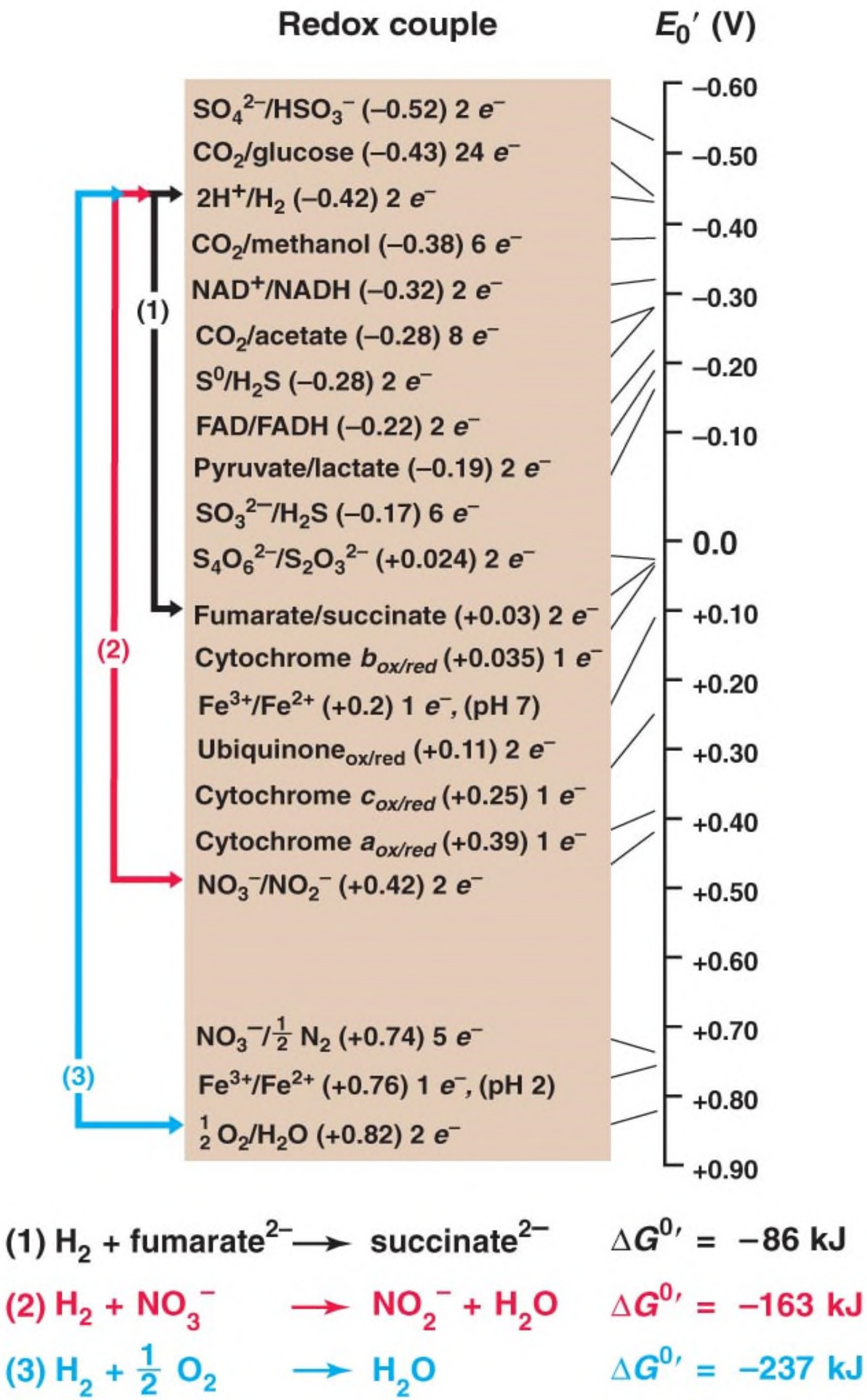
    Low C/N promoters nitrifiers growth.

    $NH_4^+ + 2O_2 = NO_3^- + H_2O + 2H^+$ (2 steps)
  - De-nitrification:

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



# The Redox Tower




$O_2$

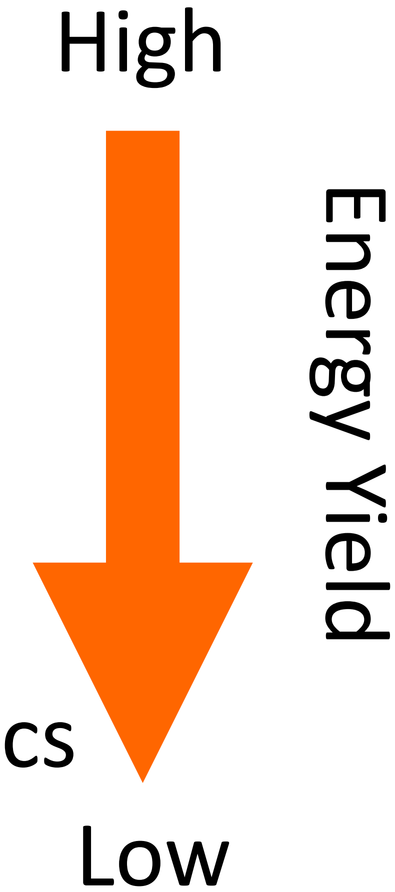
$NO_3^-$

Fe (III)

Mn (IV)

$SO_4^{2-}$

$CO_2$, Organics



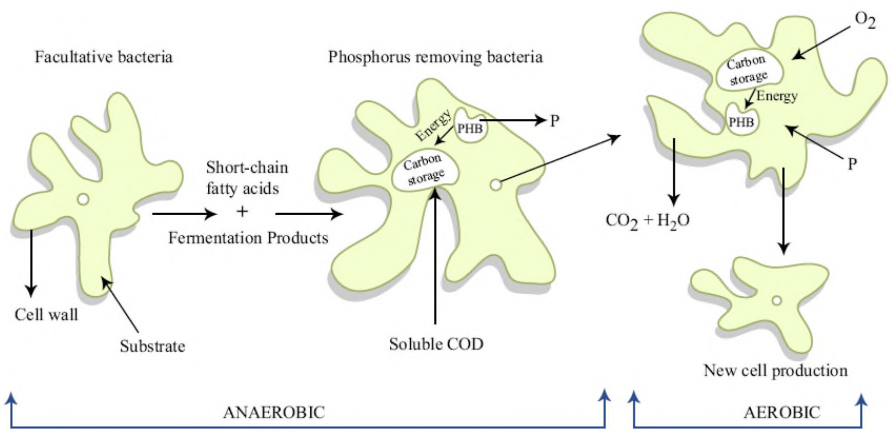

Electron Acceptor Use – Preferred Order to degrader organic contaminants

# Biological Phosphorus removal

- Biological phosphorous removal is less cost and less sludge production than chemical precipitation.

- Phosphate is essential fraction of all bacteria (1-2%): e.g. DNA, cell membrane. Phosphorus is accumulated by PAOs (phosphorus accumulating organisms).

- PAOs are favoured by alternating anaerobic/aerobic conditions. The key to success of P removal is encouraging the growth of PAOs.

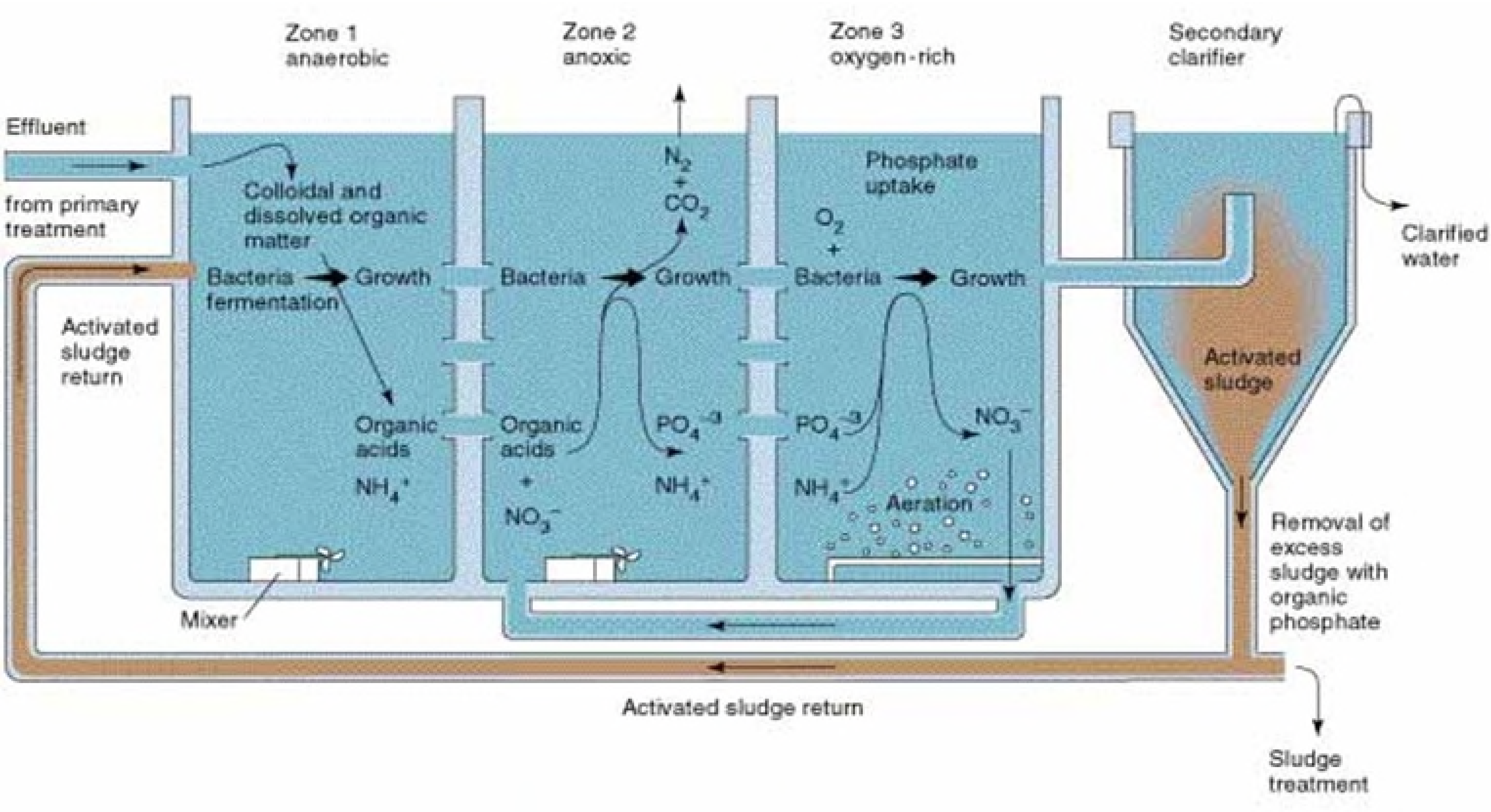



Removal mechanisms for excess biological phosphorus (COD = chemical oxygen demand, PHB = poly-β-hydroxybutyrate).

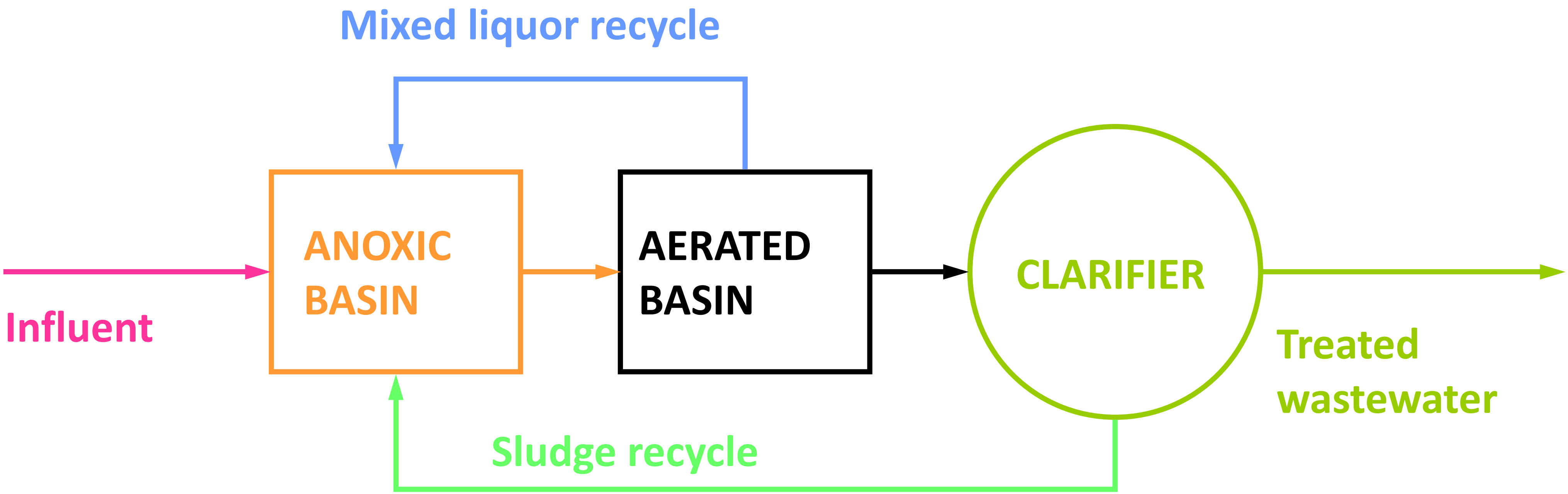
1. Anaerobic, select PAOs: release P, PAOs growing;
2. Aerobic store P as poly-P within cells.
3. Remove P-enriched cells in wasted sludge – P is removed along with cells.

# A/A/O activated sludge process

- Anaerobic zone: organics decomposition, release of phosphorus
- Anoxic zone: organics decomposition, denitrification, and absorption of phosphorus
- Aerobic zone: Nitrification and absorption of excess phosphorus



# Two stage activated sludge process




| | | |
|---|---|---|
| **Main reactions** | **ANOXIC: nitrate reduction to nitrogen gas** | **AEROBIC: ammonia Oxidation to nitrate** |
| | **COD and thiocyanate oxidation** | **COD removal** |

# Advantages of two-stage process

- Reduced overall oxygenation requirement
- Reduced alkalinity requirement – partial supply of alkalinity from the denitrification process
- No requirement for external carbon source

# Treatment efficiency

- COD removal 86-90%
- Thiocyanate removal >99%
- Phenol removal ~99.9%

# What you should now know

- Understand kinetics of biological treatment.
- Understand the sludge age is the key to determine the treatment effect
- Principle of N and P removal

# Further reading

- Chapter 8-1 to 8-5. Metcalf and Eddy (1991) Wastewater Engineering, McGraw.. ISBN: 0070416907