Fundamentals of biological treatment I

Objectives of biological treatment

- Transform dissolved and particulate biological constituents into acceptable end products

- Capture and incorporate suspended and non-settleable colloidal solids into a biological floc or biofilm

- Transform or remove nutrients (N & P)

- In some cases, remove specific trace organic constituents and compounds

Biodegradation of organic matter

- For heterotrophic, aerobic bacteria:

$$\nu_1\ (organic\ material) + \nu_2 O_2 + \nu_3 NH_3 + \nu_4 {PO_4}^{3-}$$

$$\xrightarrow{\text{microorganisms}} \nu_5\ (new\ cells) + \nu_6 CO_2 + \nu_7 H_2O$$

- Oxidize organic materials (reduced carbon) to obtain energy for the production of new cells

Oxidation-reduction reaction

- Or, redox reaction
- Involves the transfer of electrons from an electron donor to an electron acceptor
- **Respiratory metabolism**: generating energy by enzyme-mediated electron transport to an external e^- acceptor

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

e^- donor **e^- acceptor**

- **Fermentative metabolism**: use an internal e^- acceptor
  - Less energy efficient than respiration, lower growth rates

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

Types of biological processes

- Aerobic vs. anoxic vs. anaerobic
  - **Aerobic**: presence of dissolved oxygen (O_2)
  - **Anoxic**: absence of O_2, but presence of combined oxygen (usually NO_3^- & NO_2^-)
  - **Anaerobic**: absence of both O_2 and combined oxygen

- Suspended growth vs. attached growth processes

Biological treatment processes for WWTPs

Type	Common name	Use
Aerobic processes:		
Suspended growth	Activated sludge	CBOD removal, nitrification
	Aerated lagoon	CBOD removal, nitrification
	Aerobic digestion	Stabilization, CBOD removal
	Membrane bioreactor	CBOD removal, nitrification
	Nitritation process	Nitritation
Attached growth	Biological aerated filters	CBOD removal, nitrification
	Moving bed bioreactor	CBOD removal, nitrification
	Packed-bed reactors	CBOD removal, nitrification
	Rotating biological contactors	CBOD removal, nitrification
	Trickling filters	CBOD removal, nitrification
	Trickling filter/activated sludge	CBOD removal, nitrification
	Integrated fixed film activated sludge (IFAS)	CBOD removal, nitrification

Biological treatment processes for WWTPs

Type	Common name	Use
Anoxic processes:		
Suspended growth	Suspended-growth denitrification	Denitrification
Attached growth	Attached growth denitrification filter	Denitrification
Anaerobic processes:		
Suspended growth	Anaerobic contact processes	CBOD removal
	Anaerobic digestion	Stabilization, solids destruction, pathogen kill
	Anammox process	Denitritation, ammonia removal
Attached growth	Aeaerobic packed and fluidized bed	CBOD removal, waste stabilization, denitrification
Sludge blanket	Upflow anaerobic sludge blanket	CBOD removal, especially high strength wastes
Hybrid	Upflow sludge blanket/attached growth	CBOD removal

Biological treatment processes for WWTPs

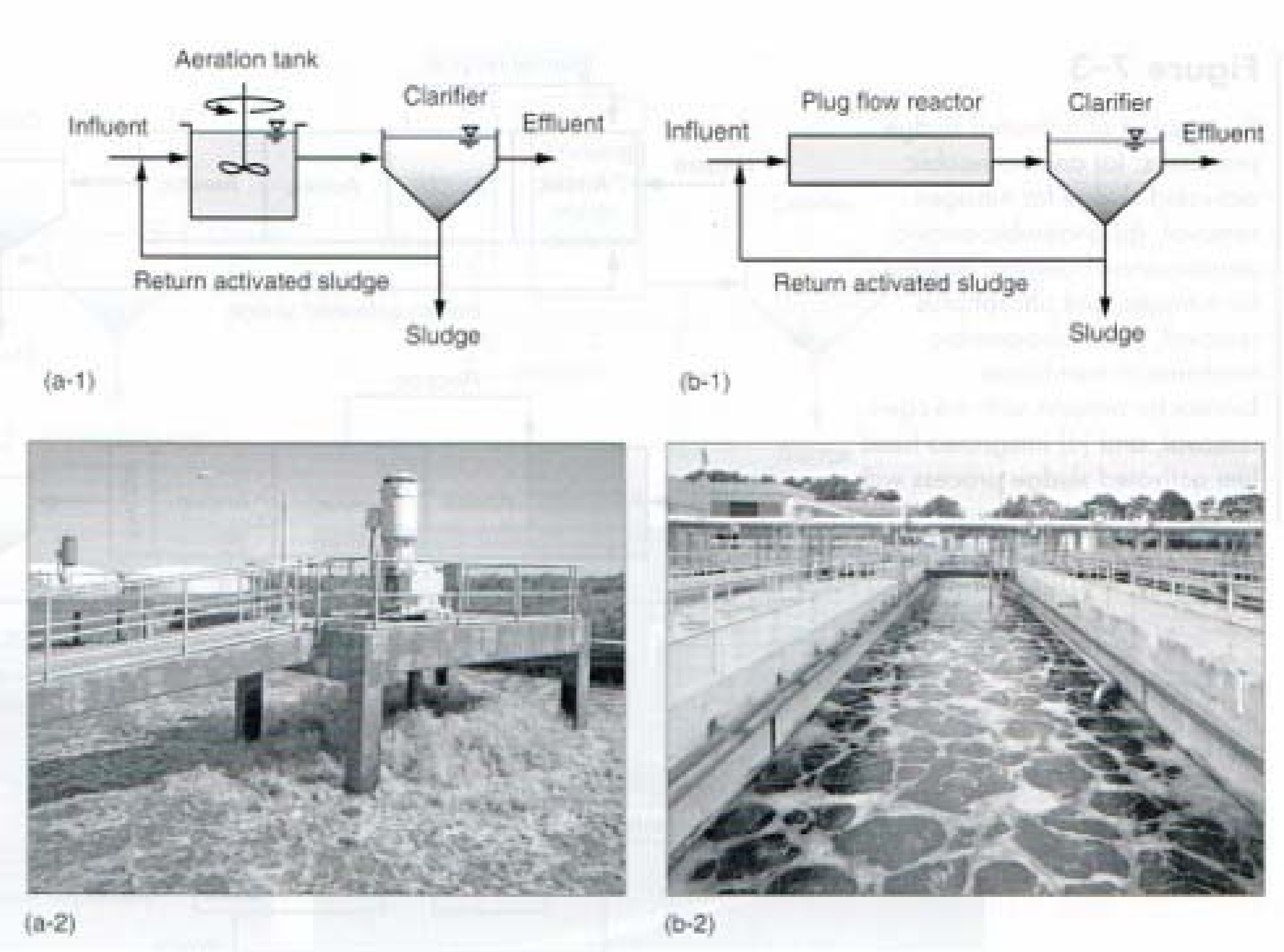
Type	Common name	Use
Combined aerobic, anoxic, and anaerobic processes:		
Suspended growth	Single- or multi-stage processes, Various proprietary processes	CBOD removal, nitrification, denitrification, and P removal
Hybrid	Single- or multi-stage suspended growth processes with fixed film media	CBOD removal, nitrification, denitrification, and P removal
Lagoon processes:		
Aerobic lagoons	Aerobic lagoons	CBOD removal, nitrification
Maturation (tertiary) lagoons	Maturation (tertiary) lagoons	CBOD removal, nitrification
Facultative lagoons	Facultative lagoons	CBOD removal, nitrification
Anaerobic lagoons	Anaerobic lagoons	CBOD removal, nitrification (waste stabilization)

Suspended growth processes

- **Microorganisms are maintained in liquid suspension by appropriate mixing methods**

- **Activated sludge process**
  - A suspended growth process
  - Most common for municipal wastewater treatment
  - First developed around 1910's
  - Named so because it involves the production of an activated mass of microorganisms capable of degrading wastes under aerobic conditions

Activated sludge - basics



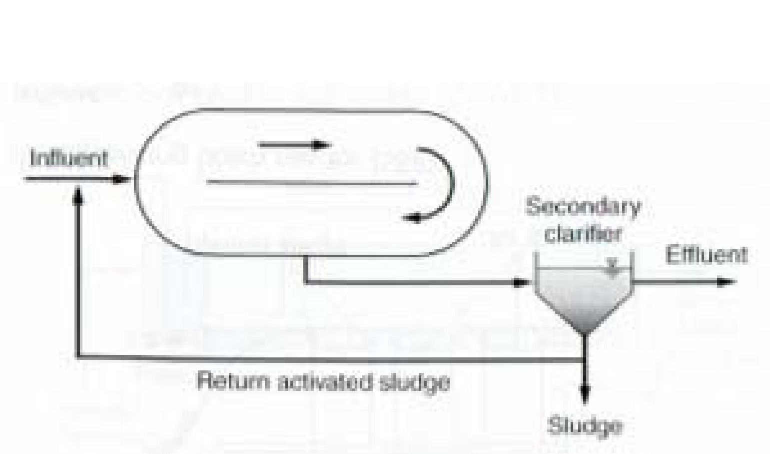
Activated sludge - basics

- **Aeration tank**
  - Influent wastewater with the microbial suspension is mixed and aerated
    - The mixture is called as “mixed liquor”
    - In activated sludge, conventionally total suspended solids are called as “mixed liquor suspended solids (MLSS)” and VSS as “mixed liquor volatile suspended solids (MLVSS)”
  - The mixed liquor then flows to a clarifier for settling
  - The settled biomass, called “activated sludge” is returned to the aeration tank
  - A portion of the settled biomass is removed daily or periodically

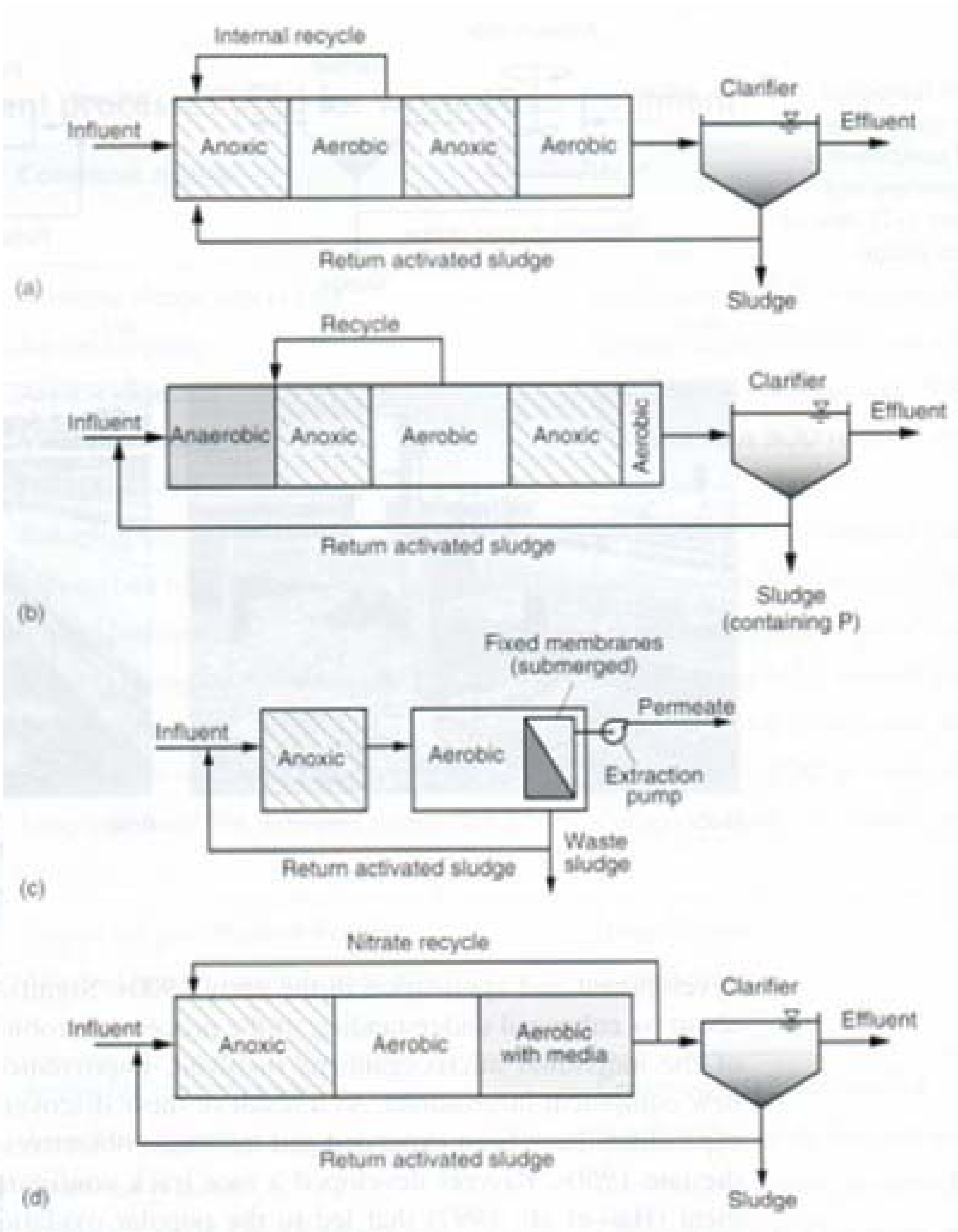
Activated sludge - modifications

- **Lots of modifications and varieties were made to activated sludge processes due to**
  - Improvements in understanding of microorganisms, aeration technology, etc.
  - Enhanced effluent quality, nutrient removal, etc.
  - Develop most suitable processes at certain conditions
  - Resolve operational problems

- **Examples**
  - Oxidation ditch – less energy intensive
  - Biological selectors – prevent filamentous growth that causes settling problems
  - Staged reactor configurations – improve biological nutrient removal
  - Membrane bioreactor (MBR) – use of membranes for liquid-solid separation



<Oxidation ditch>

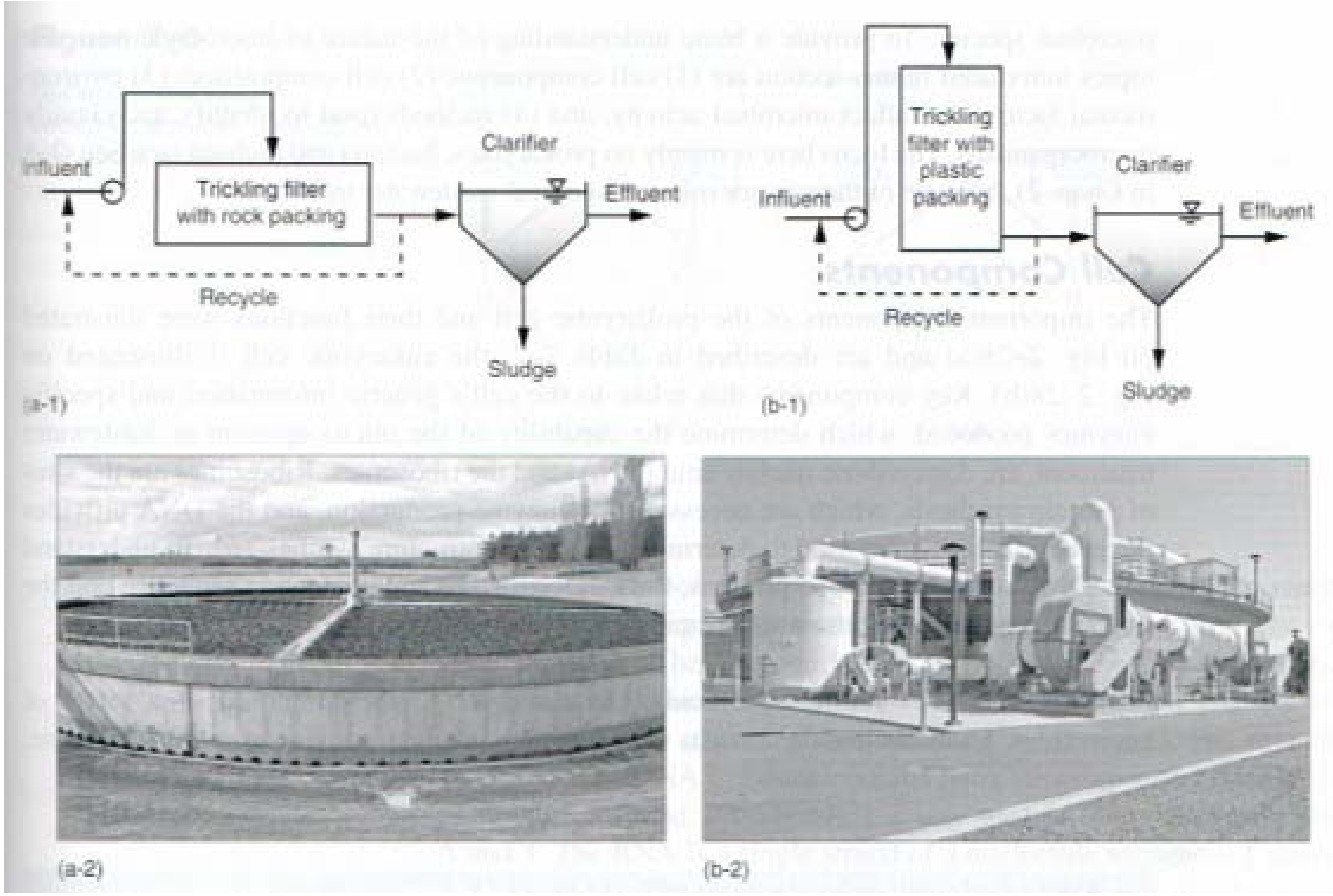


Progression of activated sludge processes: (a) anoxic-aerobic activated sludge for nitrogen removal, (b) anaerobic-anoxic-aerobic-anoxic-aerobic process for nitrogen and phosphorus removal, (c) anoxic-aerobic treatment in membrane bioreactor process with nitrogen removal, and (d) integrated fixed film activated sludge process with nitrogen removal.

Attached growth processes

- Microorganisms are **attached to an inert** packing material
- The organic material and nutrients are removed from the wastewater flowing past the attached growth (**biofilm**)
- Packing materials
  - Rock, gravel, slag, sand, redwood, plastics, etc.
- Aerobic vs. anaerobic
- Completely submerged vs. partially submerged vs. non-submerged
- Most common: **trickling filter**

Trickling filters



Attached growth biological treatment process: (a-1) schematic and (a-2) view of trickling filter with rock packing; and (b-1) schematic and (b-2) view of covered tower trickling filter with plastic packing. The air injection and odor control facilities are shown on the foreground. The tower filter is 10 m high and 50 m in diameter.

Biomass growth and yield

- **Biomass yield**
  - The ratio of the amount of biomass produced to the amount of substrate consumed

$$Biomass\ yield, Y = \frac{g\ \ biomass\ produced}{g\ \ substrate\ consumed}$$

- **Measuring biomass growth**
  - Usually MLVSS is used as a measure of biomass concentration
    - Simple and rapid measurement
    - Biomass comprise a significant portion of VSS in suspended growth processes
  - Other parameters
    - Particulate COD (total COD – soluble COD)
    - Protein content, DNA content, ATP content, etc.

Microbial growth kinetics

- The performance of biological processes depends on the dynamics of substrate utilization and microbial growth
- Design and operation of biological systems requires an understanding of the biological reactions

Microbial growth kinetics: major variables

- **Organic matter**
  - Electron donor for biological growth of heterotrophic bacteria
  - What's in interest: the amount of organic compounds that can eventually be degraded by microorganisms in wastewater
  - Defined as "biodegradable COD (**bCOD**) or ultimate BOD (**UBOD**)
  - Both bCOD & UBOD are comprised of soluble, colloidal, and particulate matter
  - We will discuss mainly on the **biodegradable soluble COD** (**bsCOD**)
  - Particulate or colloidal COD must be first hydrolyzed to bsCOD before they are utilized by microorganisms as carbon & energy source

Microbial growth kinetics: major variables

- **Biomass & other suspended solids**
  - **Volatile suspended solids (VSS)** are often used as a surrogate for biomass concentration
  - In activated sludge systems, the TSS and VSS are often termed as "*mixed liquor suspended solids (MLSS)*" and "*mixed liquor volatile suspended solids (MLVSS)*", respectively
  - MLVSS (or MLSS) is not equal to the active biomass
    - The solids contain cell debris and other suspended particles
    - Some portion of the solids is non-biodegradable
    - **Non-biodegradable volatile suspended solids** (nbVSS): organics, non-degradable → derived from influent wastewater and also produced as cell debris
    - **Inert inorganic total suspended solids** (iTSS): inorganics → originate from influent wastewater

Rate of utilization of soluble substrates

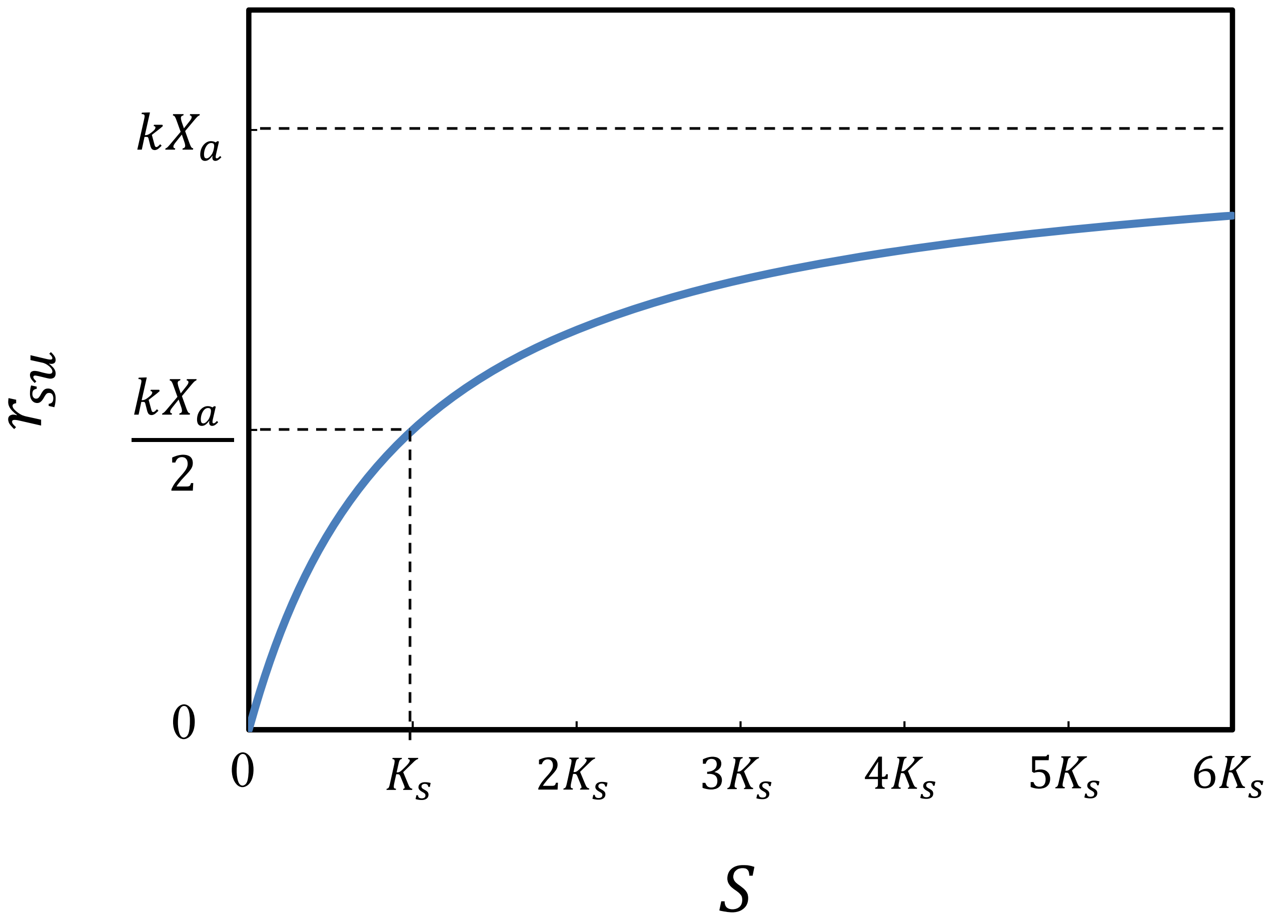
The Monod equation

$$r_{su} = \frac{kX_aS}{K_s + S}$$

r_{su} = substrate utilization rate (g/m^3-d)
k = maximum specific substrate utilization rate (g substrate/g biomass-d)
X_a= active biomass concentration (g/m^3)
S = growth-limiting substrate concentration (g/m^3)
K_s = half-velocity constant, substrate concentration at one-half the maximum specific substrate utilization rate (g/m^3)

– A "saturation-type" reaction kinetics: linear increase with S when $S \ll K_s$, approach maximum when $S \gg K_s$

Monod equation



Modeling bacterial growth

- As bacteria consume the substrate, some (specific) portion is used for energy and the other is used to produce new biomass

  (assumption)

  new growth of cells is directly proportional to the substrate utilized

- So, the bacteria growth rate from substrate utilization is expressed as:

$$r_g = \left(\frac{dX_a}{dt}\right)_{growth} = \frac{\mu_m X_a S}{K_s + S}$$

r_g = bacteria growth rate from substrate utilization (g/m^3-d)

μ_m = maximum specific bacteria growth rate (1/d)

with $r_g = Y r_{su}$ and $\mu_m = kY$

Y = true yield (g biomass/g substrate utilized)

→ This is the biomass yield we studied!

Monod equation – other forms

- The substrate utilization rate can be written as:

$$r_{su} = \frac{\mu_m X_a S}{Y(K_s + S)}$$

- Another form of Monod equation:

$$\mu = \frac{1}{X_a} \cdot \left(\frac{dX_a}{dt}\right)_{growth} = \frac{\mu_m S}{K_s + S}$$

μ = <u>specific</u> bacteria growth rate (1/d)

Biomass decay

- Microorganism concentration **<u>decrease</u>** when the substrate is depleted
- This is true in the presence of substrates as well!
- Decay (or endogenous decay endogenous respiration)
  - Cell maintenance energy needs
  - Cell lysis due to death or stress from environmental factors
  - Predation (protozoa, etc.)
  - Generally assumed to be proportional to cell concentration:

$$\left(\frac{dX_a}{dt}\right)_{decay} = -bX_a$$

X_a = active biomass concentration [M/L^3]
b = decay coefficient [T^{-1}]

  - b in the range of 0.05 ~ 0.20 d^{-1}

Net biomass growth rate

- **Net biomass growth rate**

  (net biomass growth)

  = (biomass growth according to substrate utilization) – (biomass decay)

$$r_X = Y r_{su} - b X_a = Y \frac{k X_a S}{K_s + S} - b X_a$$

r_X = net biomass growth rate (g VSS/m^3-d)

- **Net specific biomass growth rate**

$$\mu_{net} = \frac{r_X}{X_a} = Y \frac{kS}{K_s + S} - b$$

μ_{net} = net specific biomass growth rate (1/d)

Monod equation – generalized

- Actually, the Monod kinetics can be applied for any growth-limiting substrates
  - Substrates can be e^- donor, e^- acceptor, nutrients, etc.
  - Quite often the e^- donor is limiting while others are available in excess – for growth kinetics, the term substrate generally refers to e^- donor

- **Generalized equation**
  - If factors other than e^- donor can be limiting, include those as well!

Monod equation – generalized

ex) for aerobic, heterotrophic bacteria; if bsCOD, DO, and ammonia-N are limiting:

$$r_{su} = \left[\frac{\mu_{H,max} S_s}{Y_H (K_s + S_s)}\right]\left(\frac{S_o}{K_o + S_o}\right)\left(\frac{S_{NH}}{K_{NH} + S_{NH}}\right) X_{a,H}$$

$\mu_{H,max}$ = *maximum specific growth rate of heterotrophic bacteria (1/d)*

Y_H = *heterotrophic bacteria synthesis yield coefficient (g VSS/g COD used)*

$X_{a,H}$ = *active heterotrophic bacteria concentration (g VSS/m^3)*

S_i = *concentration for variable i (i = substrate, DO, ammonia-nitrogen) (g/m^3)*

K_i = *half-velocity constant for variable i (g/m^3)*

here, the term "substrate" is used for bsCOD (the e^- donor)

Typical range of parameters

Typical range/values of kinetic coefficients for activated sludge process

Coefficient	Unit	Value[a]	
		Range	Typical
k	g bsCOD/g VSS-d	4-12	6
K_s	mg/L BOD	20-60	30
	mg/L bsCOD	5-30	15
Y	mg VSS/mg BOD	0.4-0.8	0.6
	mg VSS/mg COD	0.4-0.6	0.45
b	1/d	0.06-0.15	0.10

[a]At 20°C, from Metcalf & Eddy / Aecom