

# **Fundamentals of biological treatment I**

# Fundamentals of biological treatment I

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- General overview
- Typical biological treatment processes used in wastewater treatment plants (WWTPs)
- Microbial growth kinetics

# Objectives of biological treatment

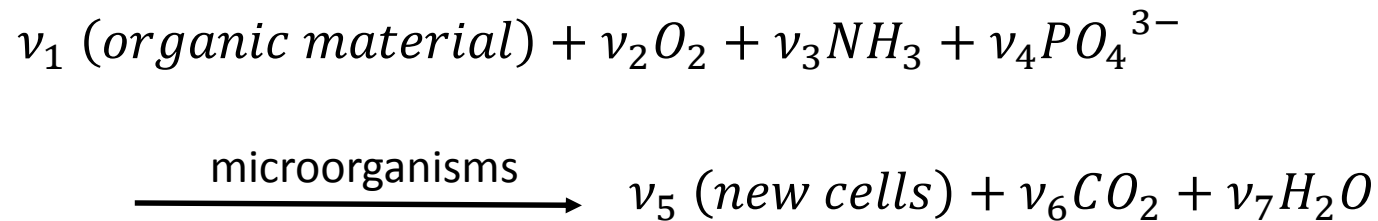
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- Transform dissolved and particulate biological constituents into acceptable end products
- Capture and incorporate suspended and non-settleable colloidal solids into a biological floc or biofilm
- Transform or remove nutrients (N & P)
- In some cases, remove specific trace organic constituents and compounds

# Biodegradation of organic matter

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- For heterotrophic, aerobic bacteria:

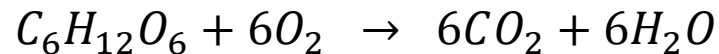


- Oxidize organic materials (reduced carbon) to obtain energy for the production of new cells

# Oxidation-reduction reaction

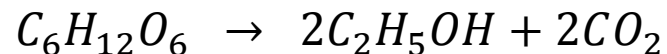
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- Or, redox reaction
- Involves the transfer of electrons from an electron donor to an electron acceptor
- **Respiratory metabolism:** generating energy by enzyme-mediated electron transport to an external e<sup>-</sup> acceptor



e<sup>-</sup> donor    e<sup>-</sup> acceptor

- **Fermentative metabolism:** use an internal e<sup>-</sup> acceptor
  - Less energy efficient than respiration, lower growth rates



# Types of biological processes

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- 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

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Type	Common name	Use
<b>Aerobic processes:</b>		
Suspended growth	Activated sludge	CBOD removal, nitrification
	Aerated lagoon	CBOD removal, nitrification
	Aerobic digestion	Stabilization, CBOD removal
	Membrane bioreactor	CBOD removal, nitrification
	Nitrification process	Nitrification
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

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# Biological treatment processes for WWTPs

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Type	Common name	Use
<b>Anoxic processes:</b>		
Suspended growth	Suspended-growth denitrification	Denitrification
Attached growth	Attached growth denitrification filter	Denitrification
<b>Anaerobic processes:</b>		
Suspended growth	Anaerobic contact processes Anaerobic digestion	CBOD removal Stabilization, solids destruction, pathogen kill
Attached growth	Anammox process Aeaerobic packed and fluidized bed	Denitritation, ammonia removal 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

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Type	Common name	Use
<b>Combined aerobic, anoxic, and anaerobic processes:</b>		
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
<b>Lagoon processes:</b>		
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)

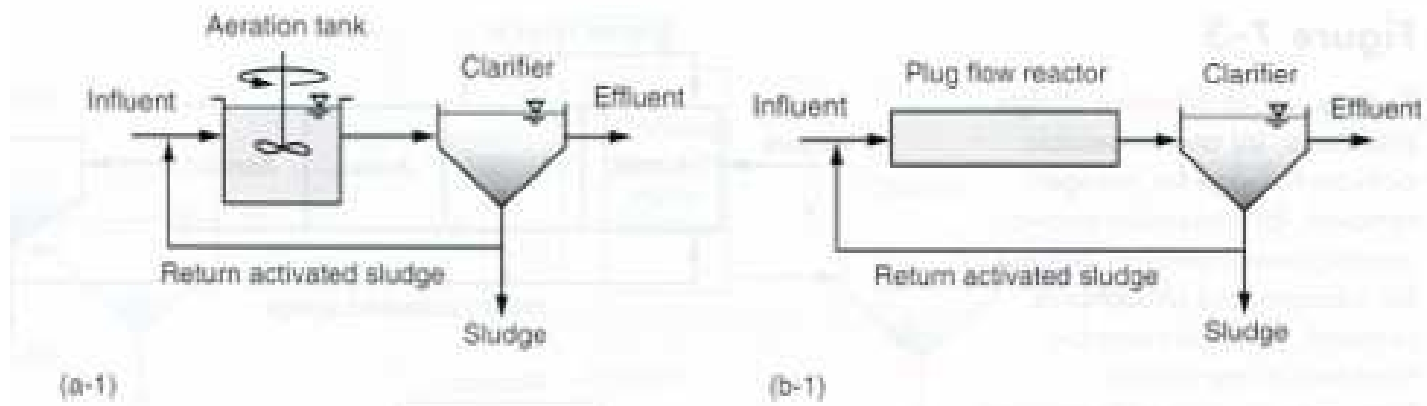
# Suspended growth processes

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- **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

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#1

(a-2)

(b-2)

# Activated sludge - basics

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- **Aeration tank**

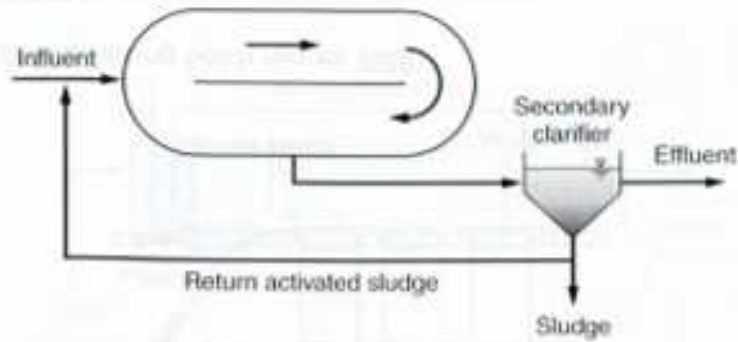
- Influent wastewater with the microbial suspension is mixed and aerated
  - The mixture is called as “mixed liquor”
  - In activated sludge, conventionally total suspended solids are called as “mixed liquor suspended solids (MLSS)” and VSS as “mixed liquor volatile suspended solids (MLVSS)”
- The mixed 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

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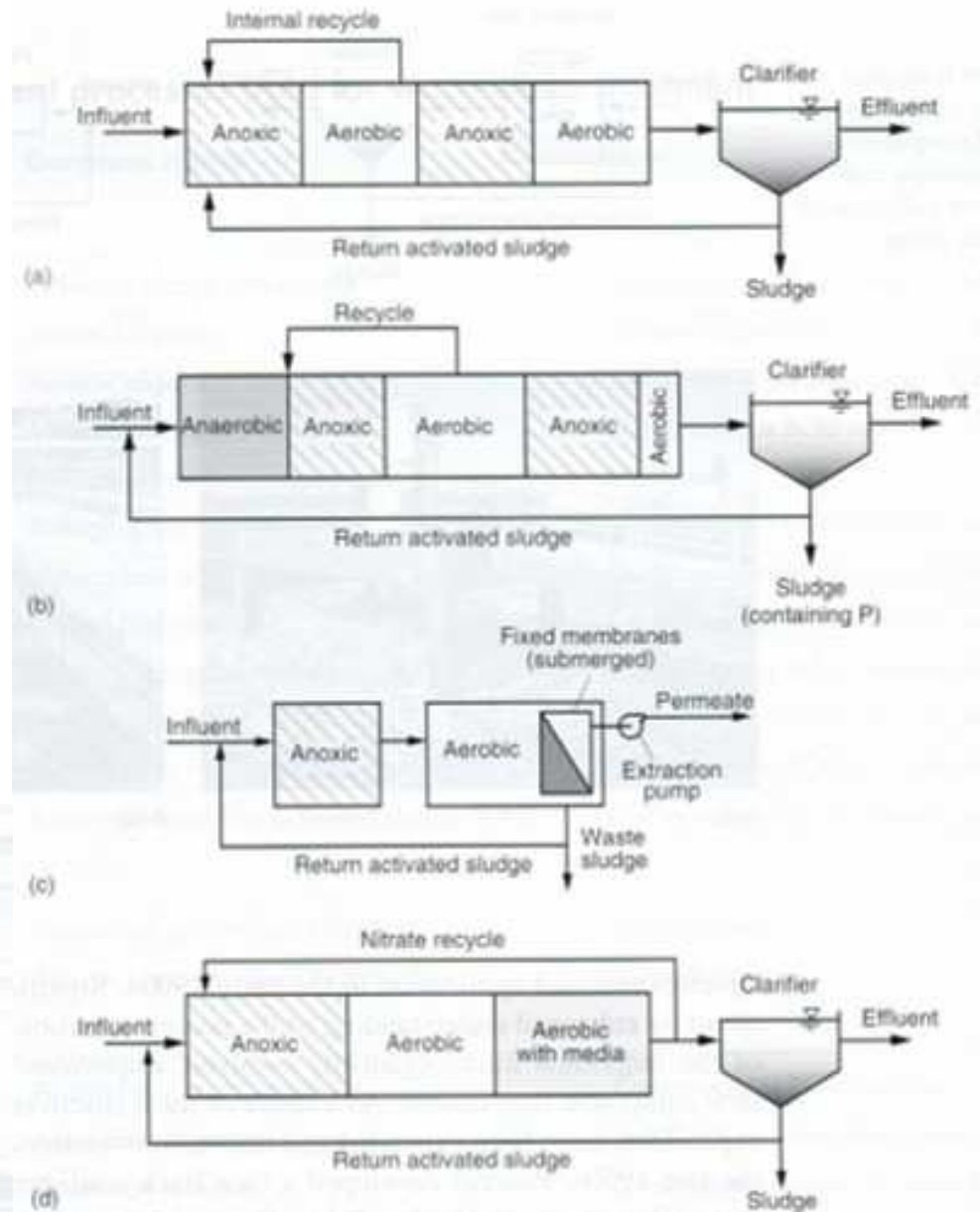
- **Lots of modifications and varieties were made to activated sludge processes due to**
  - Improvements in understanding of microorganisms, aeration technology, etc.
  - Enhanced effluent quality, nutrient removal, etc.
  - Develop most suitable processes at certain conditions
  - Resolve operational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

#2



<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.



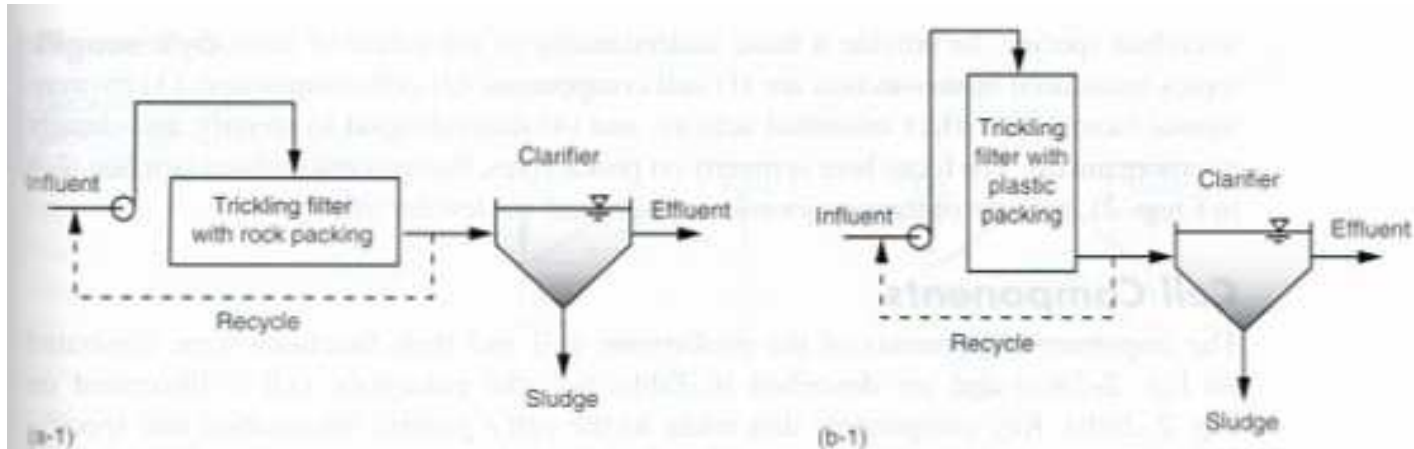
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# Attached growth processes

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- 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 yield

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- The ratio of the amount of biomass produced to the amount of substrate consumed

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

# Microbial growth kinetics: major variables

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- **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

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- **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

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## The Monod equation

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

$r_{su}$  = substrate utilization rate (g/m<sup>3</sup>-d)

$k$  = maximum specific substrate utilization rate (g substrate/g biomass-d)

$X_a$  = active biomass concentration (g/m<sup>3</sup>)

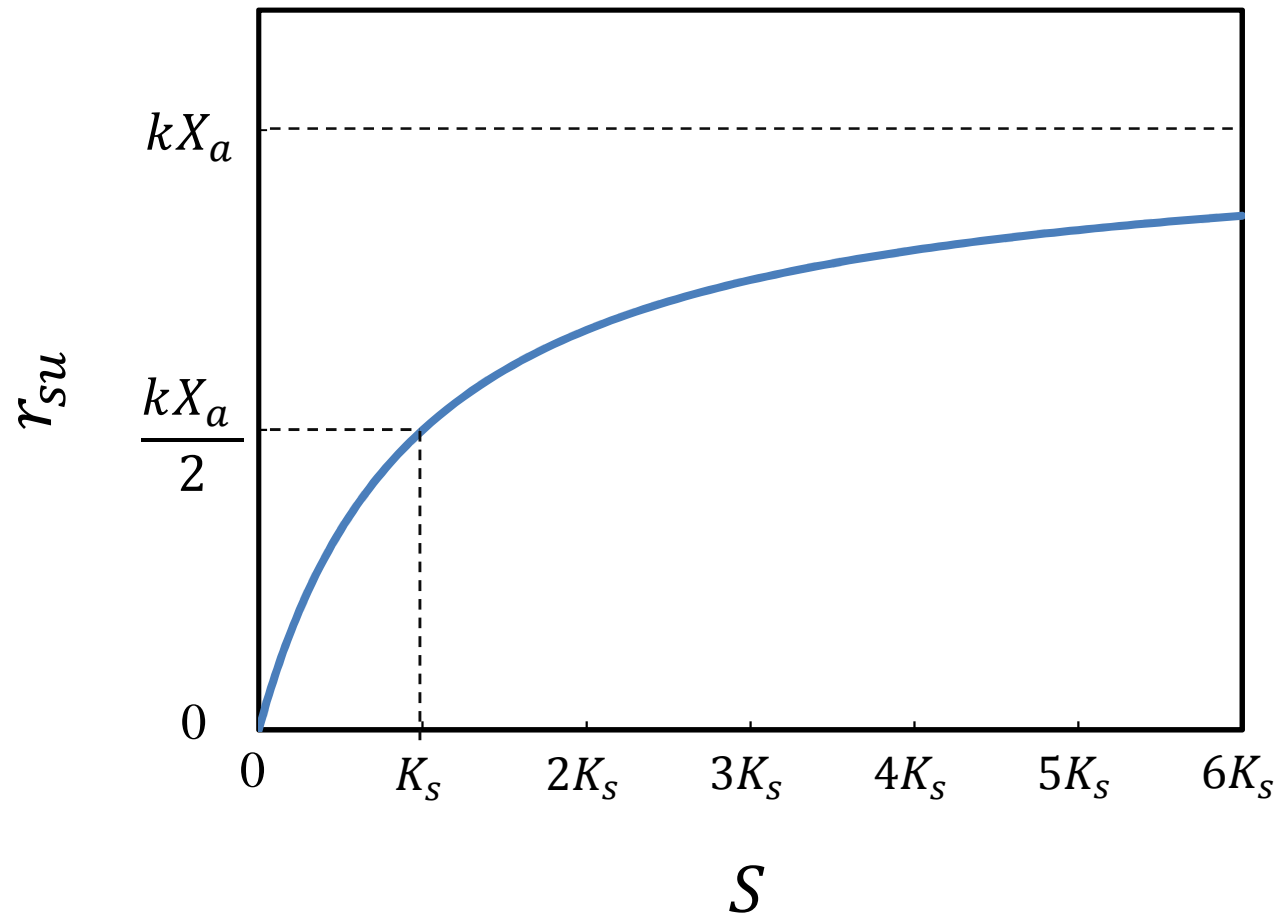
$S$  = growth-limiting substrate concentration (g/m<sup>3</sup>)

$K_s$  = half-velocity constant, substrate concentration at one-half the maximum specific substrate utilization rate (g/m<sup>3</sup>)

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

# Monod equation

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# Modeling bacterial growth

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- 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<sup>3</sup>-d)

$\mu_m$  = 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

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- 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:

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

$\mu =$ *specific bacteria growth rate (1/d)*

# Biomass decay

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- Microorganism concentration decrease 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:

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

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

- $b$  in the range of  $0.05 \sim 0.20 \text{ d}^{-1}$



# Net biomass growth rate

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- **Net biomass growth rate**  
*(net biomass growth)*  
*= (biomass growth according to substrate utilization) – (biomass decay)*

$$\begin{aligned} r_X &= Yr_{su} - bX_a \\ &= Y \frac{kX_a S}{K_s + S} - bX_a \end{aligned}$$

$r_X$  = net biomass growth rate (g VSS/m<sup>3</sup>-d)

- **Net specific biomass growth rate**

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

$\mu_{net}$  = net specific biomass growth rate (1/d)

# Monod equation – generalized

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- 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

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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<sup>3</sup>)

$S_i$  = concentration for variable  $i$  ( $i$  = substrate, DO, ammonia-nitrogen) (g/m<sup>3</sup>)

$K_i$  = half-velocity constant for variable  $i$  (g/m<sup>3</sup>)

here, the term “substrate” is used for bsCOD (the e<sup>-</sup> donor)

# Typical range of parameters

Typical range/values of kinetic coefficients for activated sludge process

Coefficient	Unit	Value <sup>a</sup>	
		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

<sup>a</sup>At 20°C, from Metcalf & Eddy / Aecom

# References

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*#1, #2, #3, #4) Metcalf & Eddy, Aecom (2014) Wastewater Engineering: Treatment and Resource Recovery, 5<sup>th</sup> ed. McGraw-Hill, p. 559, 789, 560, 561.*