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:

\[ n_1 \text{(organic material)} + n_2 O_2 + n_3 NH_3 + n_4 PO_4^{3-} \]

\[
\text{microorganisms} \quad \rightarrow \quad n_5 \text{(new cells)} + n_6 CO_2 + n_7 H_2O
\]

- 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

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

\(<e^- \text{ donor to } e^- \text{ acceptor}>\)

• **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 (O₂)
  – **Anoxic**: absence of O₂, but presence of combined oxygen (usually NO₃⁻ & NO₂⁻)
  – **Anaerobic**: absence of both O₂ and combined oxygen

• Suspended growth vs. attached growth processes
# Biological treatment processes for WWTPs

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<thead>
<tr>
<th>Type</th>
<th>Common name</th>
<th>Use</th>
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<td><strong>Aerobic processes:</strong></td>
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<td>Suspended growth</td>
<td>Activated sludge</td>
<td>CBOD removal, nitrification</td>
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<td>Aerated lagoon</td>
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<td>Membrane bioreactor</td>
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<td>Nitritation process</td>
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<td>Attached growth</td>
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<td>Moving bed bioreactor</td>
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<td>Packed-bed reactors</td>
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<td>Rotating biological contactors</td>
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<td>Trickling filters</td>
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<td>Trickling filter/activated sludge</td>
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<td>Integrated fixed film activated sludge (IFAS)</td>
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<td>Suspended growth</td>
<td>Suspended-growth denitrification</td>
<td>Denitrification</td>
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<tr>
<td>Attached growth</td>
<td>Attached growth denitrification filter</td>
<td>Denitrification</td>
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<td><strong>Anaerobic processes:</strong></td>
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<td>Anaerobic digestion</td>
<td>Stabilization, solids destruction, pathogen kill</td>
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<td>Anammox process</td>
<td>Denitrification, ammonia removal</td>
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<tr>
<td>Attached growth</td>
<td>Anaerobic packed and fluidized bed</td>
<td>CBOD removal, waste stabilization, denitrification</td>
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<tr>
<td>Sludge blanket</td>
<td>Upflow anaerobic sludge blanket</td>
<td>CBOD removal, especially high strength wastes</td>
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<tr>
<td>Hybrid</td>
<td>Upflow sludge blanket/attached growth</td>
<td>CBOD removal</td>
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<td><strong>Combined aerobic, anoxic, and anaerobic processes:</strong></td>
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<tr>
<td>Suspended growth</td>
<td>Single- or multi-stage processes, Various proprietary processes</td>
<td>CBOD removal, nitrification, denitrification, and P removal</td>
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<tr>
<td>Hybrid</td>
<td>Single- or multi-stage suspended growth processes with fixed film media</td>
<td>CBOD removal, nitrification, denitrification, and P removal</td>
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<td><strong>Lagoon processes:</strong></td>
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<td>Aerobic lagoons</td>
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<td>Maturation (tertiary) lagoons</td>
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<td>CBOD removal, nitrification</td>
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<td>Anaerobic lagoons</td>
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<td>CBOD removal, nitrification (waste stabilization)</td>
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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

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

• **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, APT content, etc.
Biomass yield & O₂ req. by stoichiometry

Assuming organic matter as C₆H₁₂O₆ & cell formula as C₅H₇NO₂:

\[3C₆H₁₂O₆ + 8O₂ + 2NH₃ \rightarrow 2C₅H₇NO₂ + 8CO₂ + 14H₂O\]

1) Biomass yield
   - Molecular weight of cell: 113 g/mole
   - COD of glucose:
     \[C₆H₁₂O₆ + 6O₂ \rightarrow 6CO₂ + 6H₂O\]  \[\boxed{1.07 \text{ g COD/g glucose}}\]
   - Biomass yield:  \[Y = 0.39 \text{ g VSS/g COD}\]
Biomass yield & $O_2$ req. by stoichiometry

\[ 3C_6H_{12}O_6 + 8O_2 + 2NH_3 \rightarrow 2C_5H_7NO_2 + 8CO_2 + 14H_2O \]

2) Oxygen requirements

Consider:
- COD provided
- Biomass COD
- Any COD not completely mineralized

Biomass COD:

\[ C_5H_7NO_2 + 5O_2 \rightarrow 5CO_2 + NH_3 + 2H_2O \]

*COD of cells: 1.42 g COD/g VSS*

Biomass yield as COD: 0.56 g cell COD/g COD used
Biomass yield & O₂ req. by stoichiometry

\[
\text{Oxygen consumed} = \text{COD utilized} - \text{COD cells}
\]
\[
= 1 - 0.56 \text{ g COD/g COD used}
\]
\[
= 0.44 \text{ g O}_2/\text{g COD used}
\]

or, from \[3C_6H_{12}O_6 + 8O_2 + 2NH_3 \rightarrow 2C_5H_7NO_2 + 8CO_2 + 14H_2O\]

\[
\text{Oxygen consumed} = \frac{8(32 \text{ g O}_2/\text{mole})}{3(180 \text{ g/mole})(1.07 \text{ g COD/g glucose})}
\]
\[
= 0.44 \text{ g O}_2/\text{g COD used}
\]
The partitioning of COD (or electrons) into energy and biomass production depends on:

- Growth conditions
- Type of microorganisms
- Type of electron acceptors
- Type of electron donors
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

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

- $r_{su} =$ 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

\[ \frac{r_{su}}{2} = kX_a \]

\[ S \]

\[ 0 \quad K_s \quad 2K_s \quad 3K_s \quad 4K_s \quad 5K_s \quad 6K_s \]