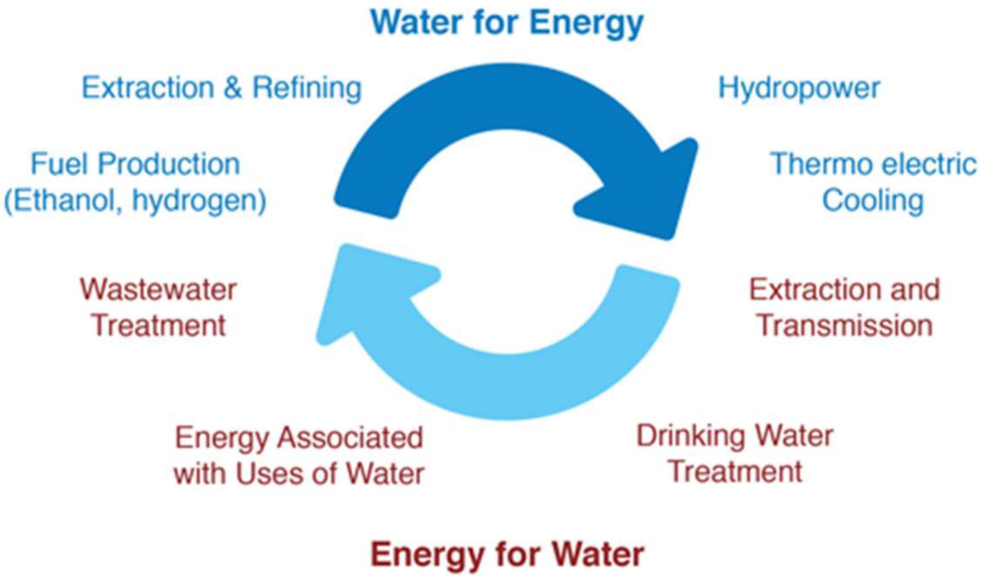
Water-energy nexus

Today's class

- What's water-energy nexus?
- **Anaerobic digestion and hydrogen fermentation**
- Microbial fuel cell
- Anammox: simultaneous removal of ammonia and nitrite (NO_2^-)

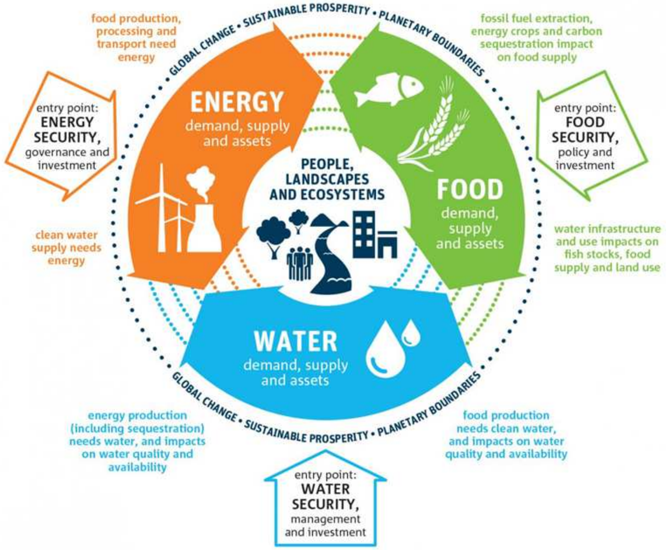
Water and energy

- Most critical resources for human life
- Water and energy often closely intercorrelated



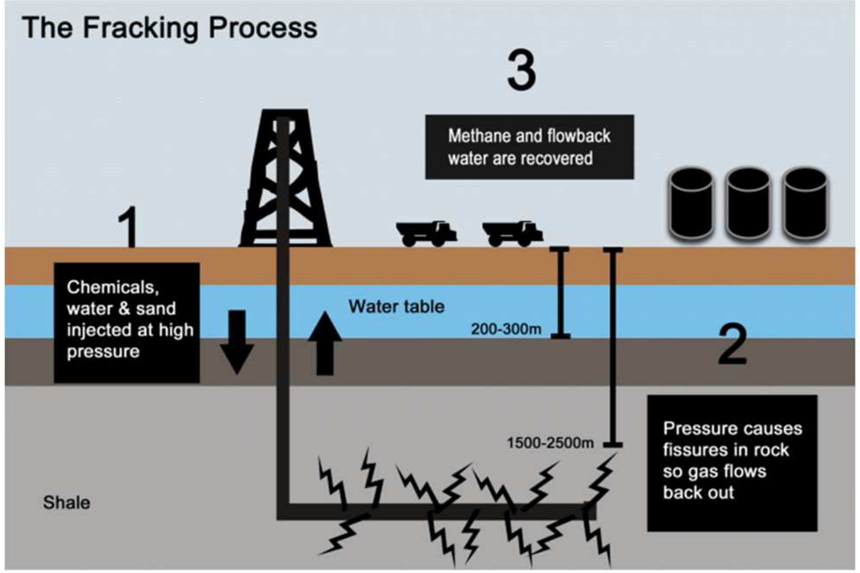
* Food -- another critical resource

- water-energy-food nexus: an extended version of water-energy nexus



Water-energy nexus

- Exploring the interlinks between water and energy
- Consider energy (efficiency, production, and recovery) in systems where water was the major concern
  - e.g., in drinking water supply, in wastewater treatment
- Consider water (quality and quantity) in systems where energy was the major concern
  - e.g., cooling water for power generation, hydraulic fracturing for oil & gas production, hydropower
- Design and operate systems to get benefit in terms of both water and energy



홍천
친환경 에너지타운

연간 폐자원 에너지를 통한 주민경제수익 1억 4천 6백만원

태양광 전력 생산, 판매 (52백만원/년)

소수력 전력 생산

도시가스공급 주민연료비 절감 (42백만원/년, 마을)

퇴액비 판매 주민수익창출 (52백만원/년)

지역경제활성화 마을환경개선

Anaerobic digestion

- **Applications**
  - Treatment of waste sludge & high-strength organic wastes
- **Advantage**
  - Low biomass yield
  - Energy production in the form of methane (of recent interest!)
    - WWTP -- ~3% of total energy cost in USA
    - Target on energy positive treatment of wastewater
- **Disadvantage**
  - Effluent quality usually not as good as aerobic treatment

Before construction (Jan 15)

After construction (Feb 18)

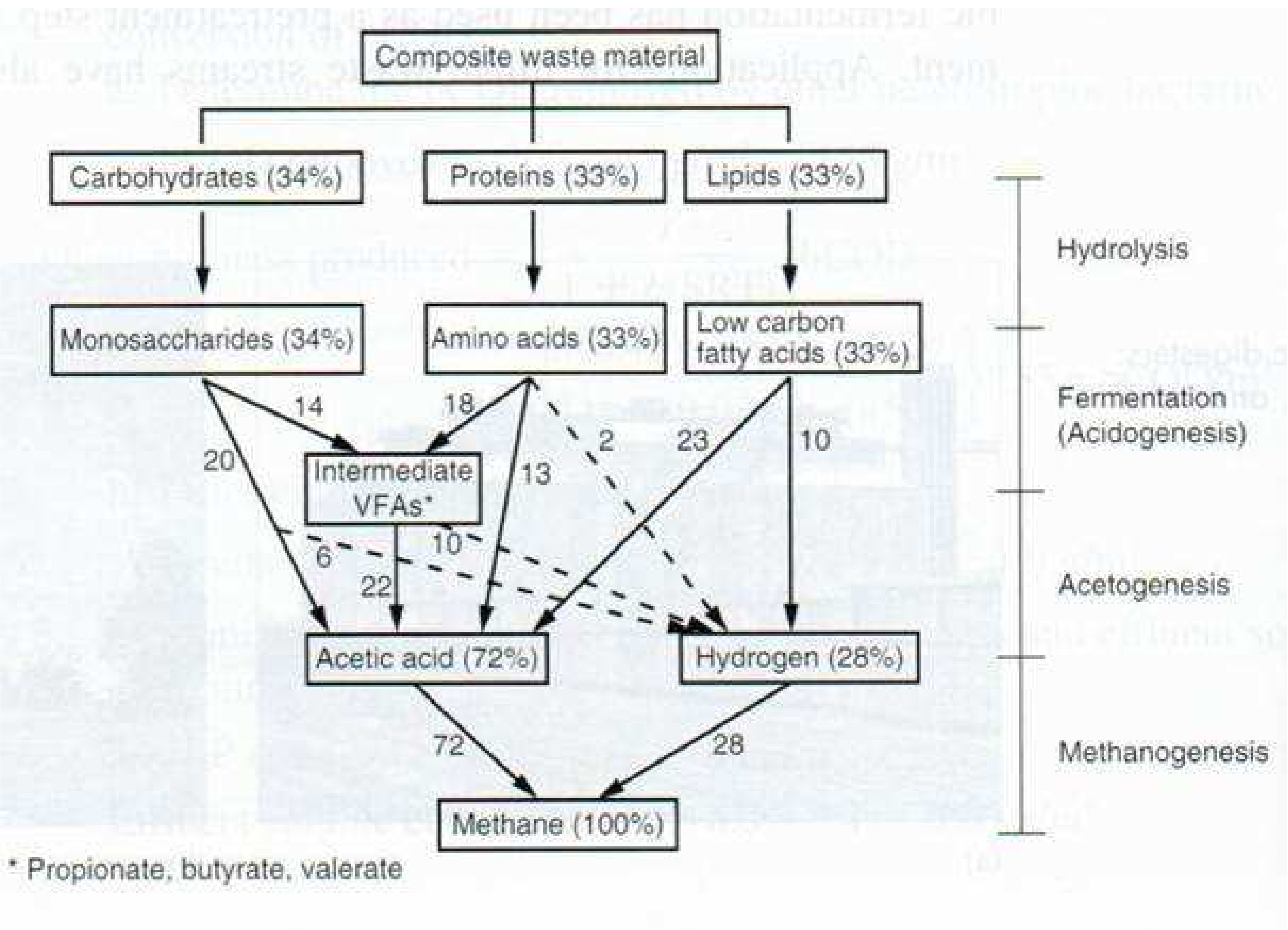
Hongchun energy town, Korea
(animal manure + food waste)

Anaerobic digestion tank

Biogas storage tank

Suyeong wastewater treatment plant,
Busan, Korea
(sewage sludge)

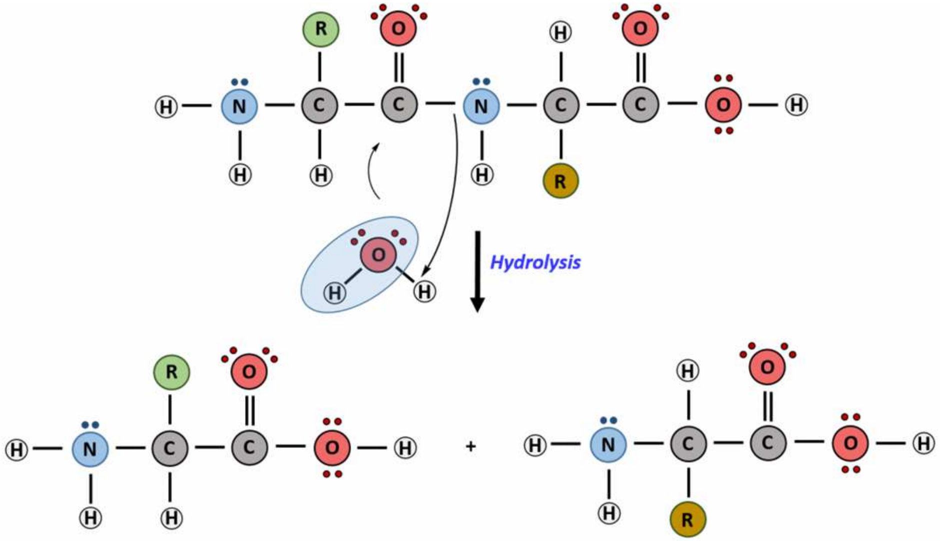
Anaerobic digestion: Key steps



* Propionate, butyrate, valerate

Anaerobic digestion: Key steps

- **Hydrolysis**
  - Particulates - - - -→ Soluble molecules - - - -→ Monomers
  - By extracellular enzymes
- **Acidogenesis (fermentation)**
  - Use: sugars, amino acids, fatty acids (both e- donor & acceptor)
  - Produce: VFAs, CO_2, H_2
- **Acetogenesis**
  - Use: VFAs other than acetate
  - Produce: acetate, H_2, CO_2



Anaerobic digestion: Key steps & syntrophy

- **Methanogenesis**
  - By methanogens (belongs to domain **Archaea**)
  - Two groups of methanogens
    - *aceticlastic* methanogens: acetate → $CH_4 + CO_2$
    - *hydrogenotrophic* methanogens: $H_2 + CO_2 \rightarrow CH_4$
  - In anaerobic digestion process, ~72% methane from acetic acid & ~28% from H_2 (→ gas production of ~65% CH_4 & ~35% CO_2)

- **Syntrophic relationship**
  - Methanogens – acidogens & acetogens
    - Acidogens & acetogens: produce H_2, acetate, etc.
    - Methanogens: cleans up the acido/acetogenesis end products
  - *"Interspecies hydrogen transfer"*

Process kinetics

- Low yield coefficients
  - Low energy gain by chemical transformation
  - Fermentation: Y ~ 0.06 g VSS/g COD; b ~ 0.02 d^{-1}
  - Methanogenesis: Y ~ 0.03 g VSS/g COD; b ~ 0.008 d^{-1}

- Steps determining the rate
  - Hydrolysis or methanogenesis
  - Typically hydrolysis for biomass (e.g., microorganisms, plant matter) & methanogenesis for food waste & manure

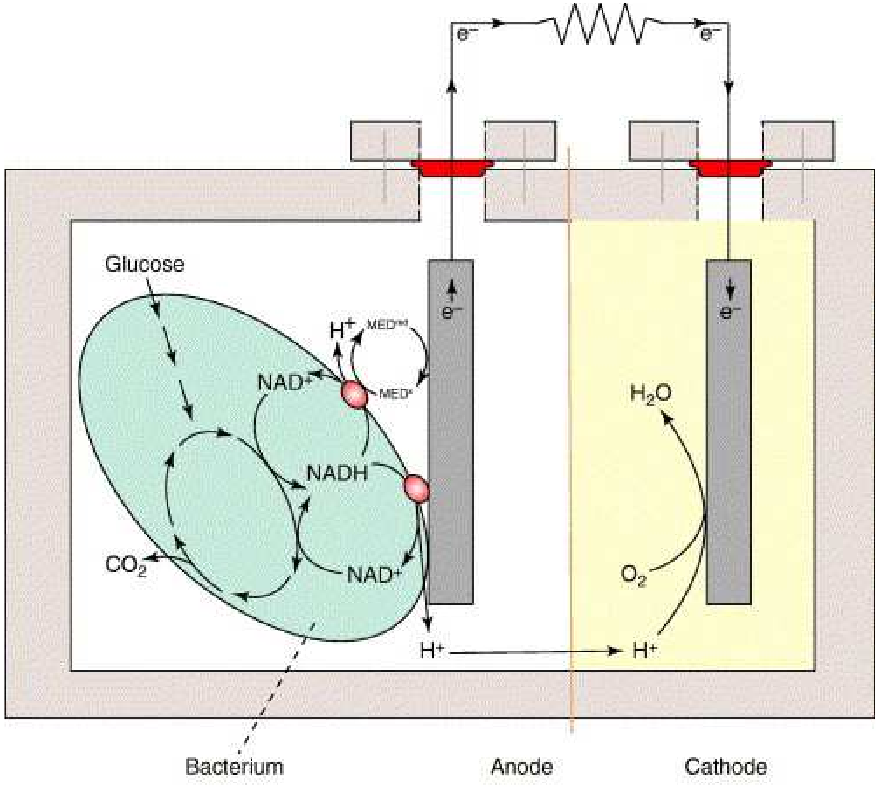
- High SRT is needed (around 40 d) due to slow degradation rate

Process stability

- Kinetics of VFA production is faster than utilization (methanogenesis)
- At steady state, sufficient methanogen population is established to maintain low VFA concentration (<200 g/m^3) & $pH \geq 7.0$
- Unstable digester operation may develop under transient loading conditions (VFA production > utilization): VFA accumulation & pH drop
- Low pH leads to decline in methanogenic activity: process failure

Microbial fuel cells (MFCs)

- A device that converts the chemical energy to electrical energy by the action of microorganisms
- The redox reaction is catalyzed by microorganisms



TRENDS in Biotechnology

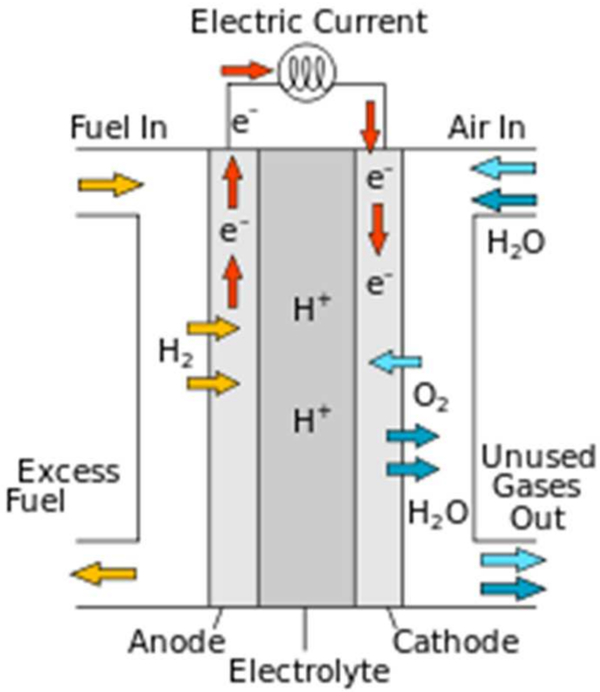
cf) Fuel cells

- A device that converts the chemical energy from a fuel into electricity through an electrochemical reaction of hydrogen with oxygen or another oxidizing agent

- Mechanism
  - At the anode

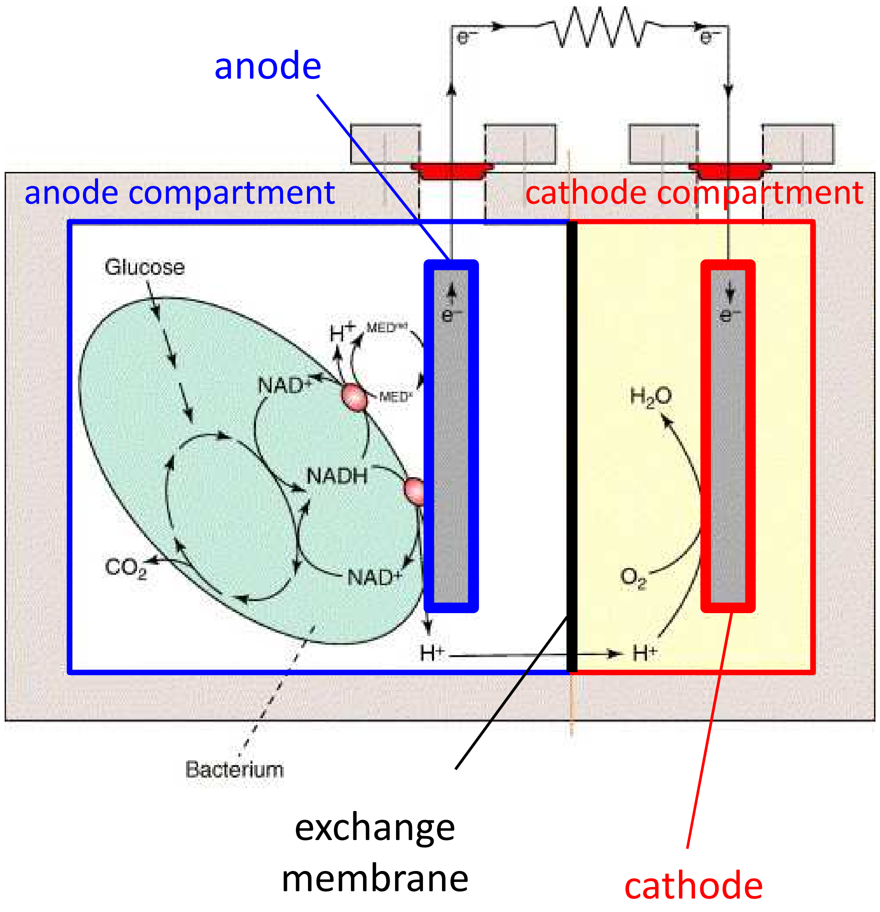
    ex) $\frac{1}{2}H_2 \rightarrow H^+ + e^-$
  - At the cathode

    ex) $\frac{1}{4}O_2 + H^+ + e^- \rightarrow 2H_2O$
  - H^+ moves through the electrolyte



Things occurring in MFCs

- At the anode compartment
  - Wastewater (or organic waste-containing water) is fed
  - Bacteria live and oxidize the organics provided
  - Should be kept low in DO
- At the cathode compartment
  - Oxygen is reduced to water
  - Catalyst (ex: Pt) is used as cathode
- Exchange membrane
  - Allows H^+ to flow from the anode compartment to cathode compartment



MFCs: pros & cons

- Advantages
  - Generation of energy out of bio-waste / organic matter
  - Direct conversion of substrate energy to electricity
  - No gas treatment required
  - Aeration may not be needed (the cathode may be passively aerated)

- Disadvantages
  - Low power density: losses of electric potential significant
  - High initial cost

Anaerobic ammonia oxidation (Anammox)

- **Anaerobic oxidation of ammonia to produce nitrogen gas**

$$NH_4{}^{+} + NO_2{}^{-} \rightarrow N_2 + H_2O$$

e^- donor *e^- acceptor*

- **Requires aerobic nitritation of ammonia to NO_2^-** for the process to occur (~55% conversion of NH_4-N to NO_2-N)

- **By autotrophic bacteria**

  → No organic carbon consumption during the process

Anammox mechanism

$$NH_4{}^+ + NO_2{}^- \rightarrow N_2 + H_2O$$

- **Proposed metabolic model** (Van de Graaf et al., 1997)
  1) Reduction of nitrite to hydroxylamine (NH_2OH)
  2) Condensation of hydroxylamine with ammonium to hydrazine (N_2H_4)
  3) Oxidation of hydrazine to nitrogen gas
- **Some formation of NO_3-N from NO_2-N**
  - To provide the reducing power to fix CO_2

$$CO_2 + 2NO_2{}^- + H_2O \rightarrow CH_2O + 2NO_3{}^-$$

- **Overall reaction** (Strous et al., 1999)

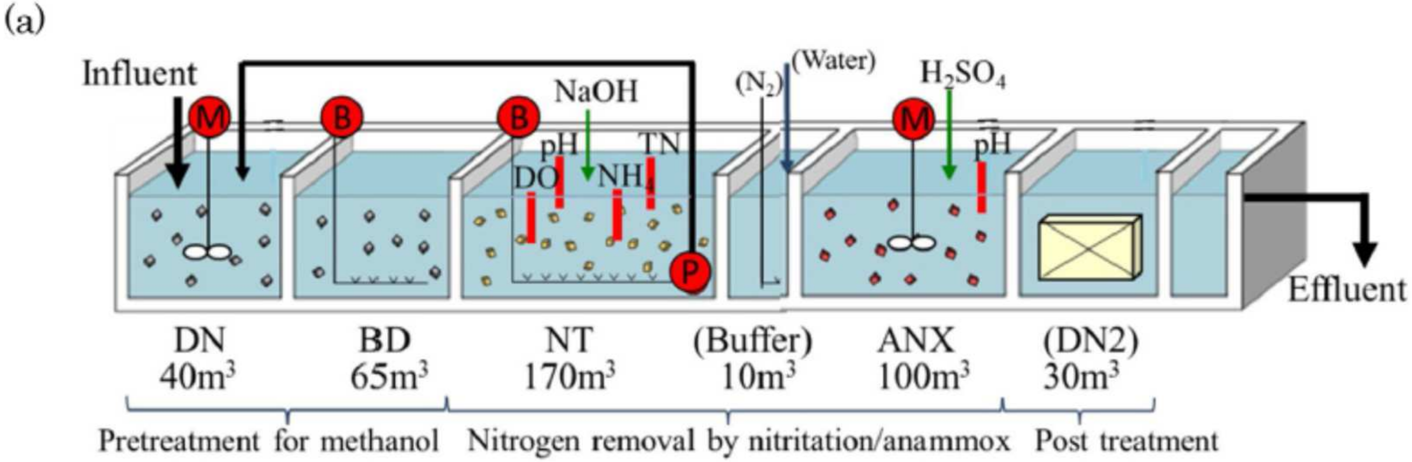
$$1.0NH_4{}^+ + 1.32NO_2{}^- + 0.066HCO_3{}^- + 0.13H^+$$
$$\rightarrow 1.02N_2 + 0.26NO_3{}^- + 0.066CH_2O_{0.5}N_{0.021} + 2.03H_2O$$

Anammox process

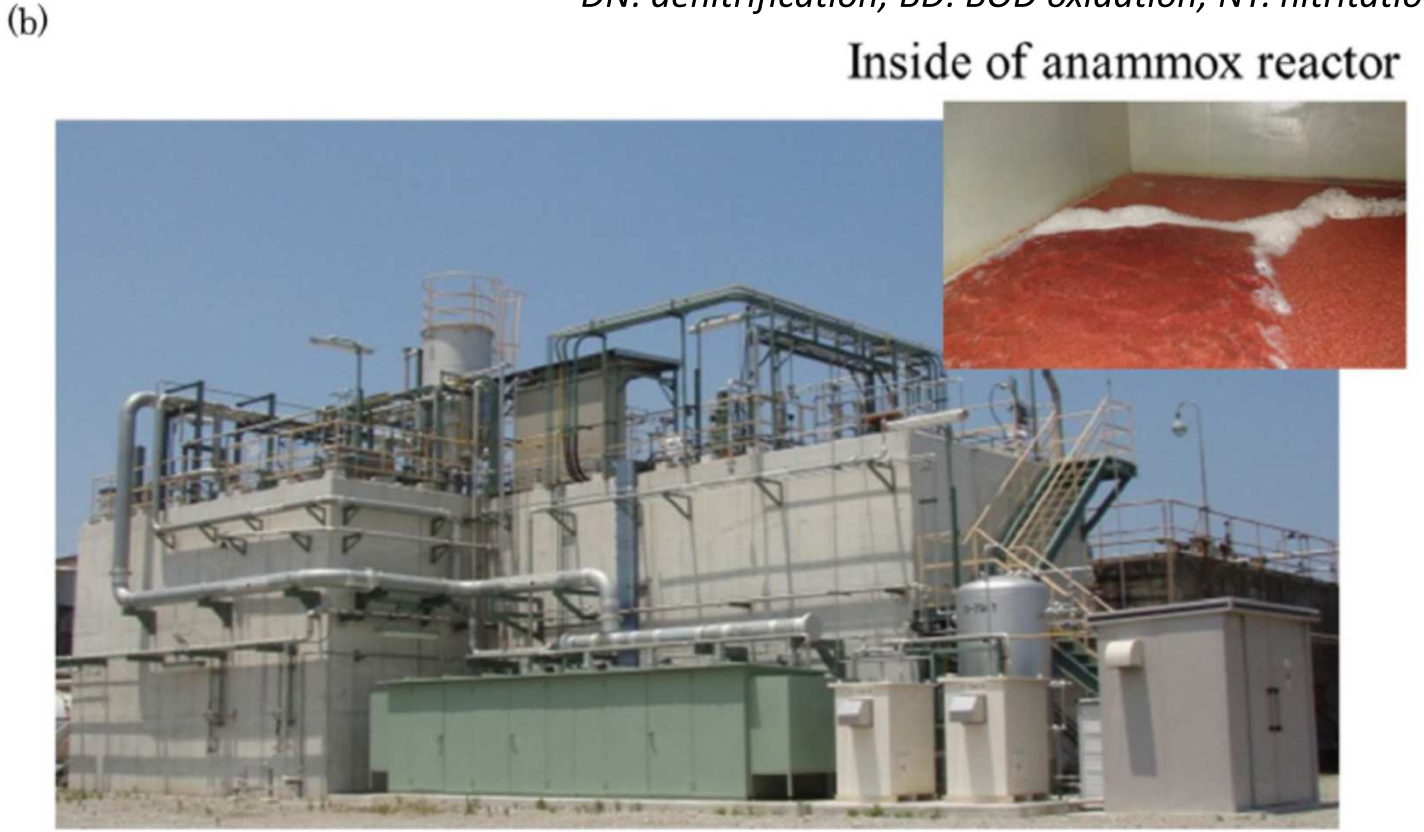
- **Microorganisms for Anammox**
  - Forms dense granular flocs
  - Slowly growing (low Y value)
  - High bacterial concentration (10^{10}~10^{11} cells/mL) should be maintained for good Anammox activity

- **Advantages**
  - Substantially lower aeration requirement → low cost, low carbon footprint
  - Low sludge production
  - Good sludge settling properties

- **Limitations/challenges**
  - Long time required for process setup/recovery after sludge loss
  - Optimum pH = 8 → may need chemical input
  - Difficult to achieve partial nitrification (nitritation)



DN: denitrification; BD: BOD oxidation; NT: nitritation; ANX: anammox



Inside of anammox reactor

Fig. 1. (a) Schematic diagram and (b) photograph of full-scale anammox plant using gel carriers.

Key references

- Textbook sec 7-11, chap 10

Next class

- Wastewater reuse
  - Non-potable reuse
  - (Direct/indirect) Potable reuse
- Introduction to SNU-CEE-EnvGroup