Innovative biological wastewater treatment processes

Anammox process

- **An**aerobic **amm**onia **ox**idation
- **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 process

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

- **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)

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

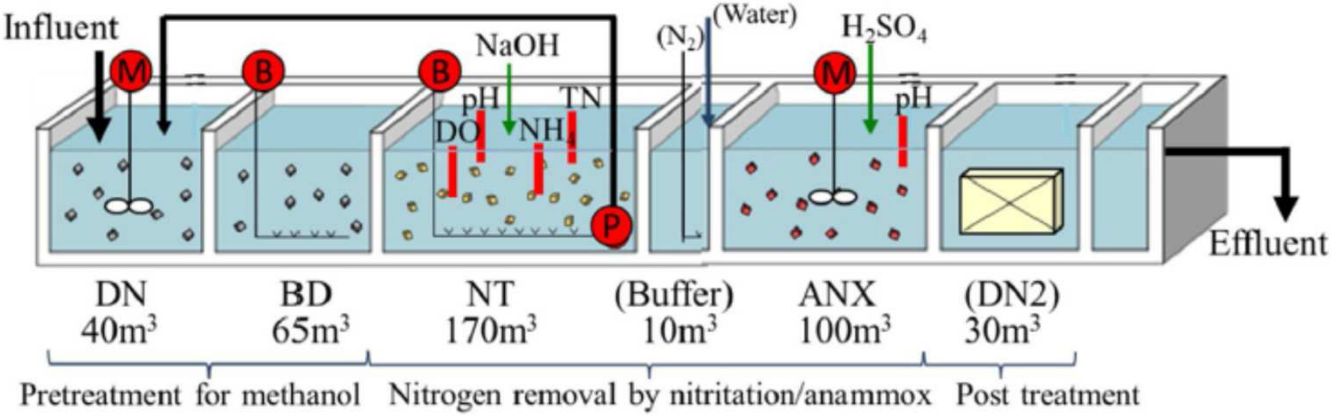
Anammox process

- **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)

(a)



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

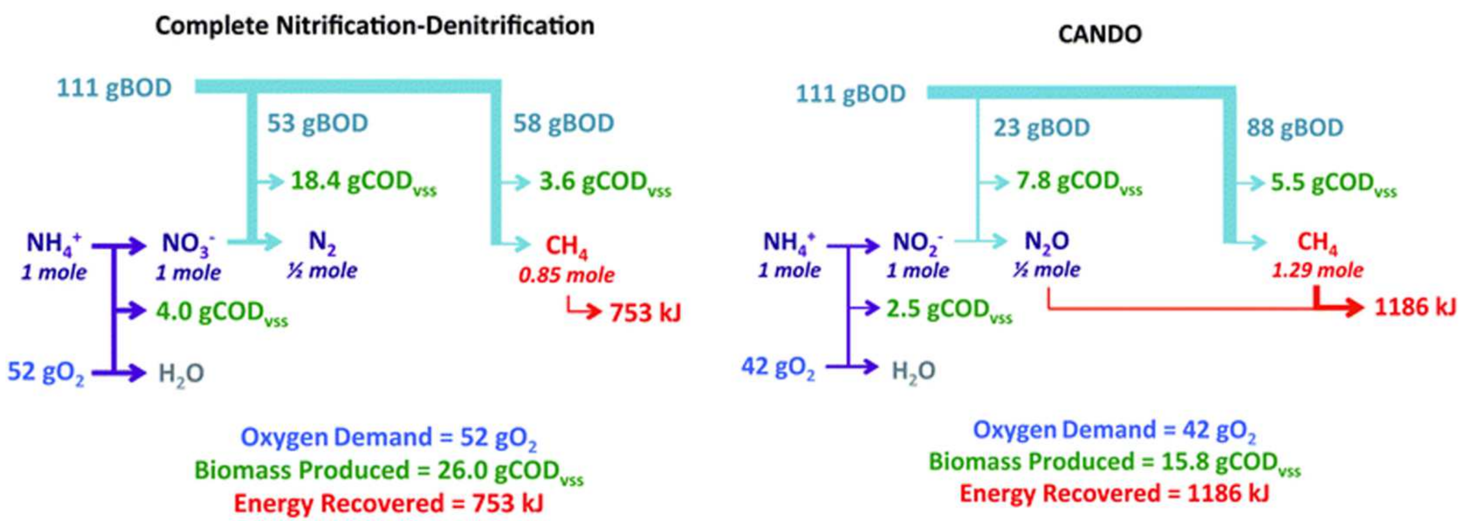
(b)

Inside of anammox reactor

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

CANDO process

- **C**oupled **A**erobic-anoxic **N**itrous **D**ecomposition **O**peration
- A recently proposed process (Scherson et al., Energy Environ. Sci., 2013)
- Three-step process
    1) Partial nitrification of NH_4^+ to NO_2^- (same as the prelim. step for anammox)
    2) **Partial anoxic reduction of NO_2^- to N_2O**
    3) N_2O conversion to N_2 with energy recovery (e.g., use as an oxidant for $CH_4 \rightarrow CO_2$)
- Pilot-scale demonstration underway



Aerobic granular sludge

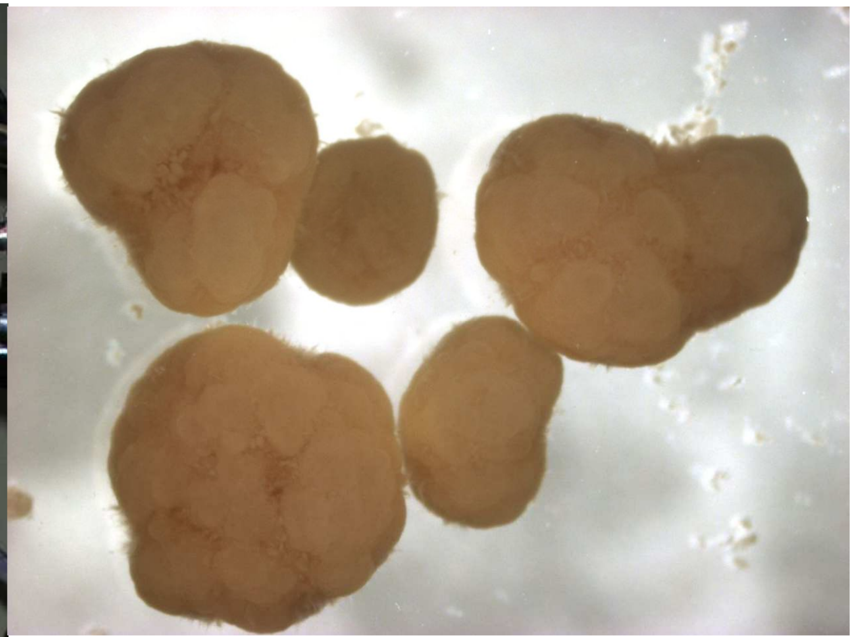
- Basic concept
  - Grow and utilize microbial **"granules"**, which are compact and dense aggregates, instead of microbial "flocs" used in conventional activated sludge

Parameter	Activated sludge	Aerobic granular sludge
Shape and average size	Irregular; Small, ~<0.2 mm	Large mm-sized distinct particles with well-defined spherical shape; >0.2 mm
Specific gravity	0.997-1.01	1.010-1.017
Settling velocity	Lower settling velocities ~<10 m/h	Higher settling velocities >10 m/h
Microenvironment within the particle	Minimum possibilities for anaerobic zones	Distinct layers or microenvironments i.e., aerobic, anaerobic and anoxic zones

Nancharaiah & Reddy Bioresour. Technol., 2018

Aerobic granular sludge: Operational scheme

- Usually employed in sequential batch reactor (SBR) settings
- Operation requirements to accomplish granulation
  - **Feast-famine feeding regimes**: expose microorganisms to alternating condition of presence/absence of organic matter → granule formers are competitive at this condition (can store organic matter in cells during the famine period)
  - **Hydrodynamic shear force**: high shear forces favor the granule formation and improve the physical granule integrity
  - **Short settling time**: selectively collect granules while flushing out flocs



Aerobic granules

SBR with aerobic granules

Aerobic granular sludge: Advantages

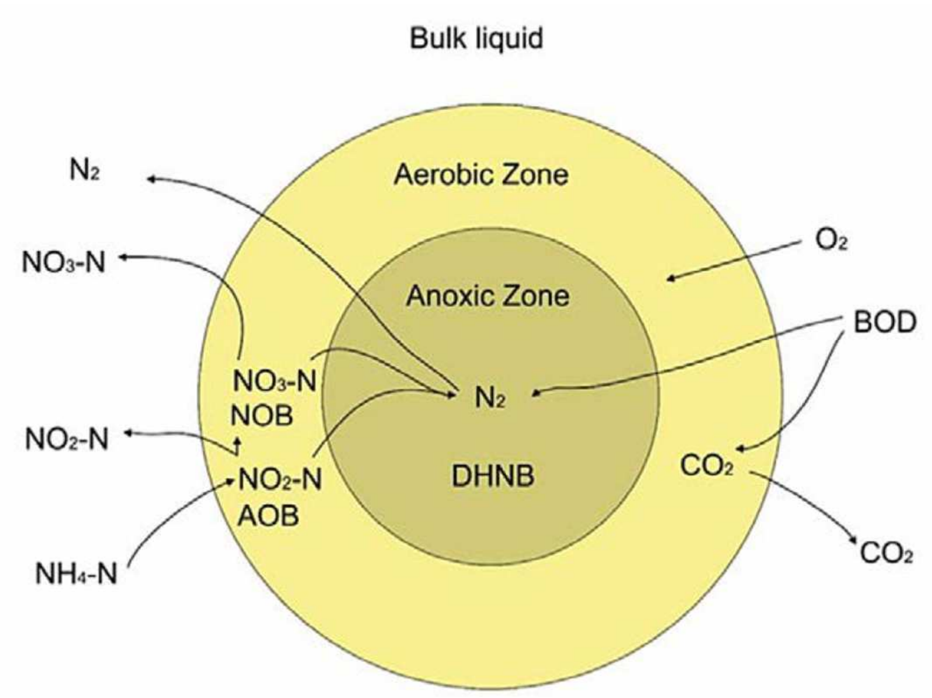
- **Stability**
  - Good performance with shock and fluctuating organic loading
- **Low energy requirement**
  - High aeration efficiency
  - Neither sludge return nor nitrate recycle streams required
- **Low space requirement**
  - High organic loading rate (OLR) due to high biomass concentration
  - Clarifier not required
- **Simultaneous removal of BOD & N/P**
  - Layer of microenvironments formed within the granule

  → simultaneous nitrification-denitrification: aerobic/anoxic

  → enhanced biological phosphorus removal (EBPR): aerobic/anaerobic

Simultaneous nitrification and denitrification

- In microbial flocs, granules, or biofilm
- Local conditions in the floc/granule/biofilm may be different from bulk liquid
  - **High DO at the exterior and low DO inside →** conditions for nitrification and denitrification may develop
- Can be significant if optimal conditions are developed



Aerobic granular sludge: Current status

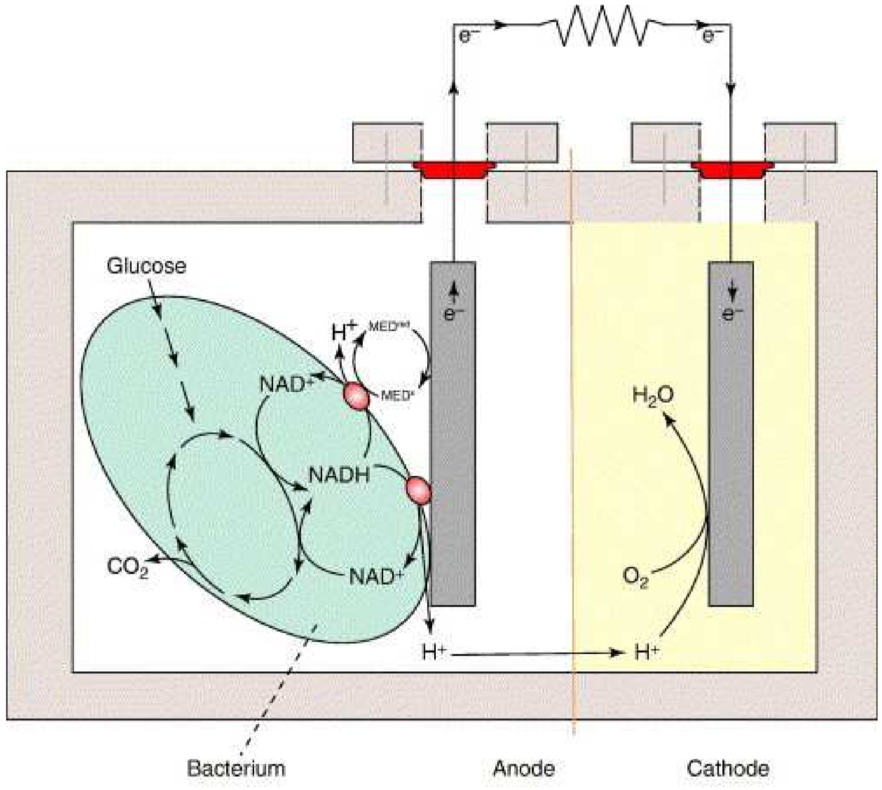
- Adapted for industrial applications from mid 2000s
- Full-scale demonstration plants in South Africa and Portugal in late 2000s
- Application for scaled-up domestic sewage treatment plants from 2010

WWTP in Epe, the Netherlands (2010~)

WWTP in Garmerwolde, the Netherlands (2010~)

Microbial Fuel Cell (MFC)

- 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

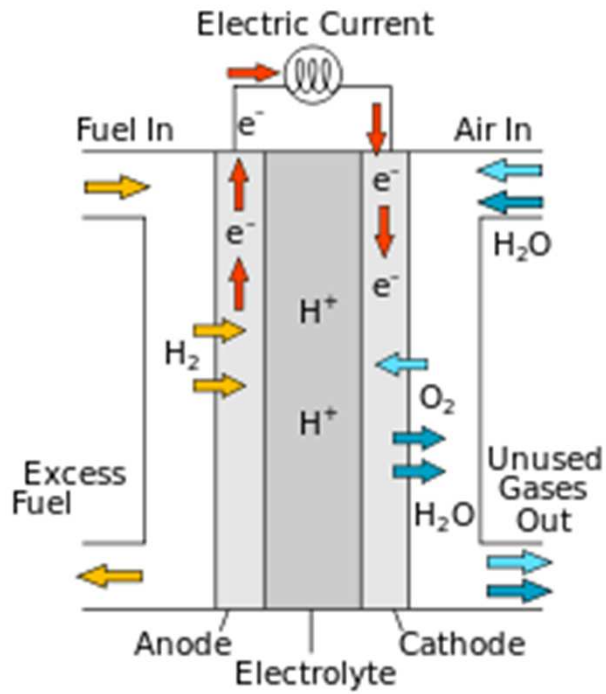
cf) Fuel cell

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

- Each half reaction of the overall redox reaction occurs separately at each electrode
  - Oxidation half reaction (Anode)

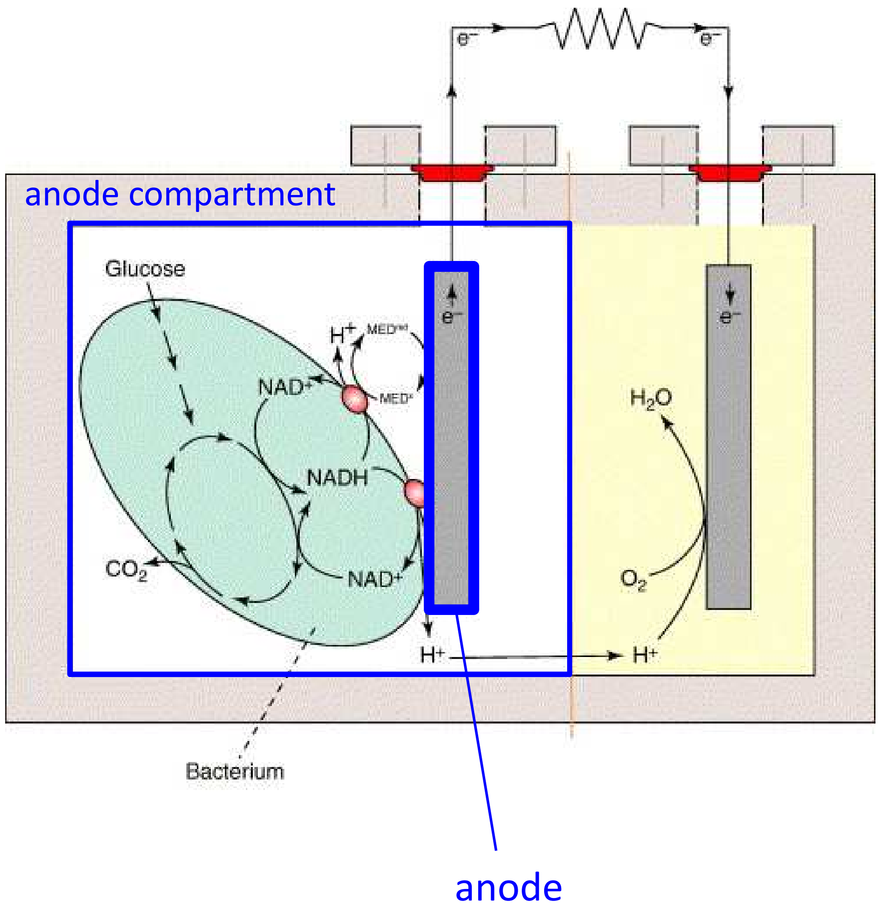
    ex) $\frac{1}{2}H_2 \rightarrow H^+ + e^-$
  - Reduction half reaction (Cathode)

    ex) $\frac{1}{4}O_2 + H^+ + e^- \rightarrow 2H_2O$
  - Electrons move through the electric circuit (electricity generated)
  - H^+ move through the electrolyte



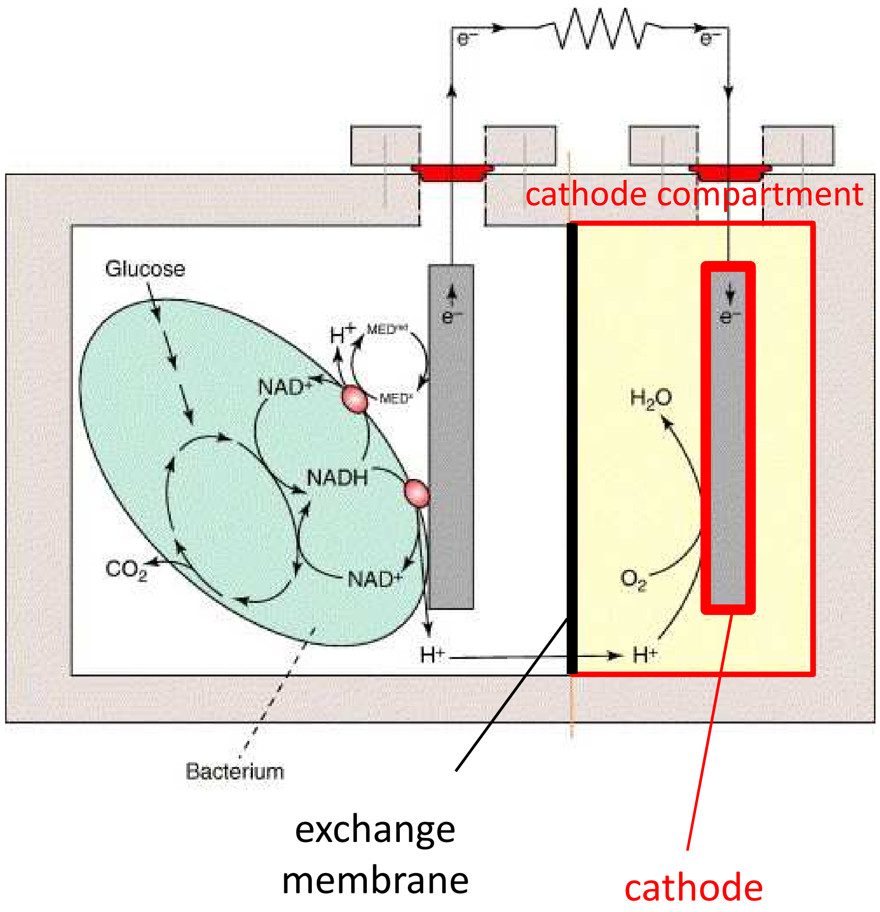
MFC – Anode compartment

- Anode
  - Should be conductive, bio-compatible, chemically stable with substrate
  - Stainless steel mesh, graphite plates or rods
- Bacteria live in the anode compartment and oxidize the substrate provided
- Anode compartment should be kept low in DO
- Substrates: usually organics – carbohydrates, protein, VFAs, cellulose, and wastewater



MFC – Cathode compartment / EM

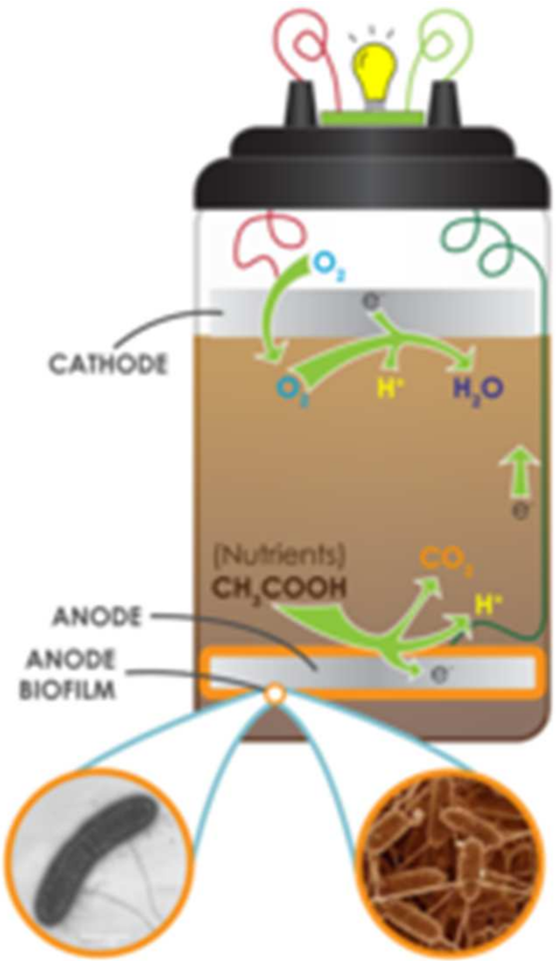
- Cathode compartment
  - Usually oxygen is used as an oxidizing agent
  - Catalysts used for the oxygen reduction reaction: Pt most common
- Exchange membrane
  - Allows proton (H^+) to flow from the anode compartment to cathode compartment



Soil-based MFCs

- Soil serves as
  - Anode compartment
  - Proton exchange membrane

- And soil provides
  - Microorganisms
  - Nutrients



MFC – 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

Microbial electrolysis cell (MEC)

- Not an electricity-generating, but electricity-consuming process to produce hydrogen or methane as a fuel
- Hydrogen is produced by reducing protons at the cathode
  - The voltage required to reduce protons is provided by: substrate utilization by microorganisms at the anode + additional voltage supply from an outside source