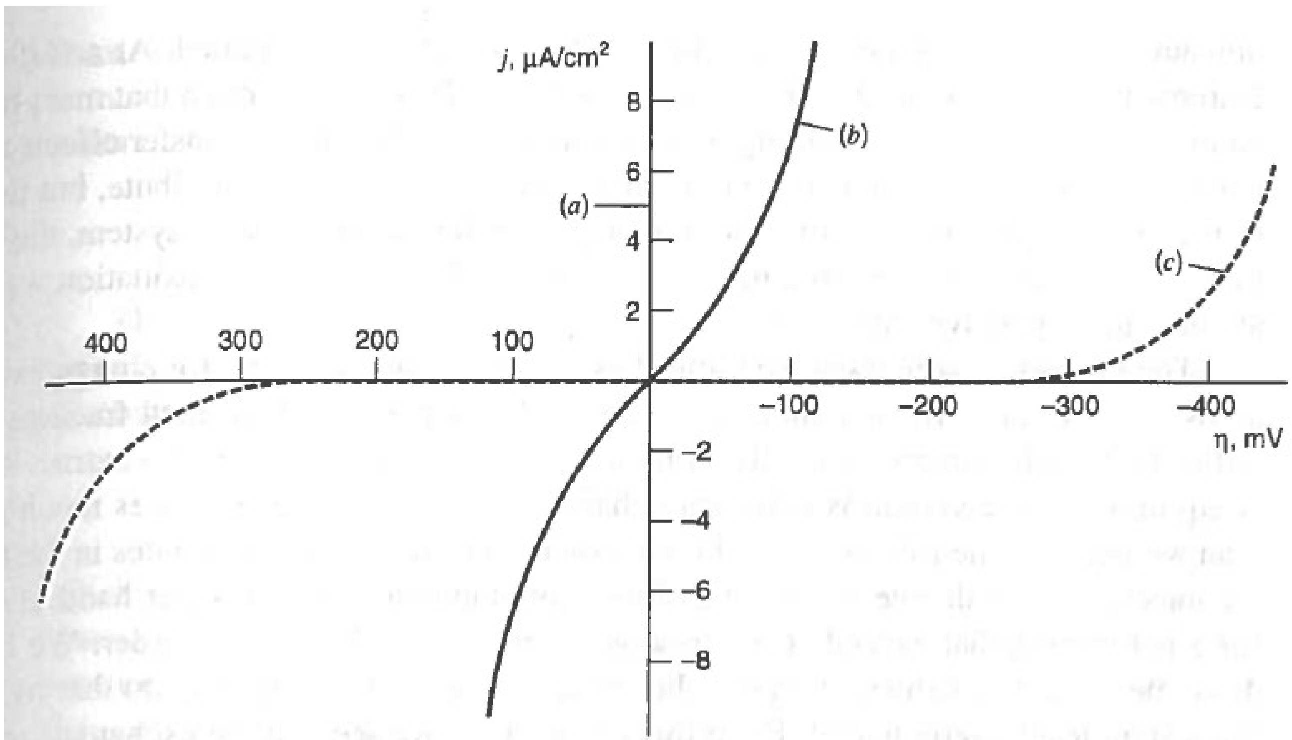
Microbial electrochemical technologies – fundamental aspects and methods of analysis

Week 4 – Microbial electrochemical reactors

- Why do we want microorganisms on electrodes?
- How do microbes accomplish electron transfer?
- Reactor design
- Applications
- Historical development

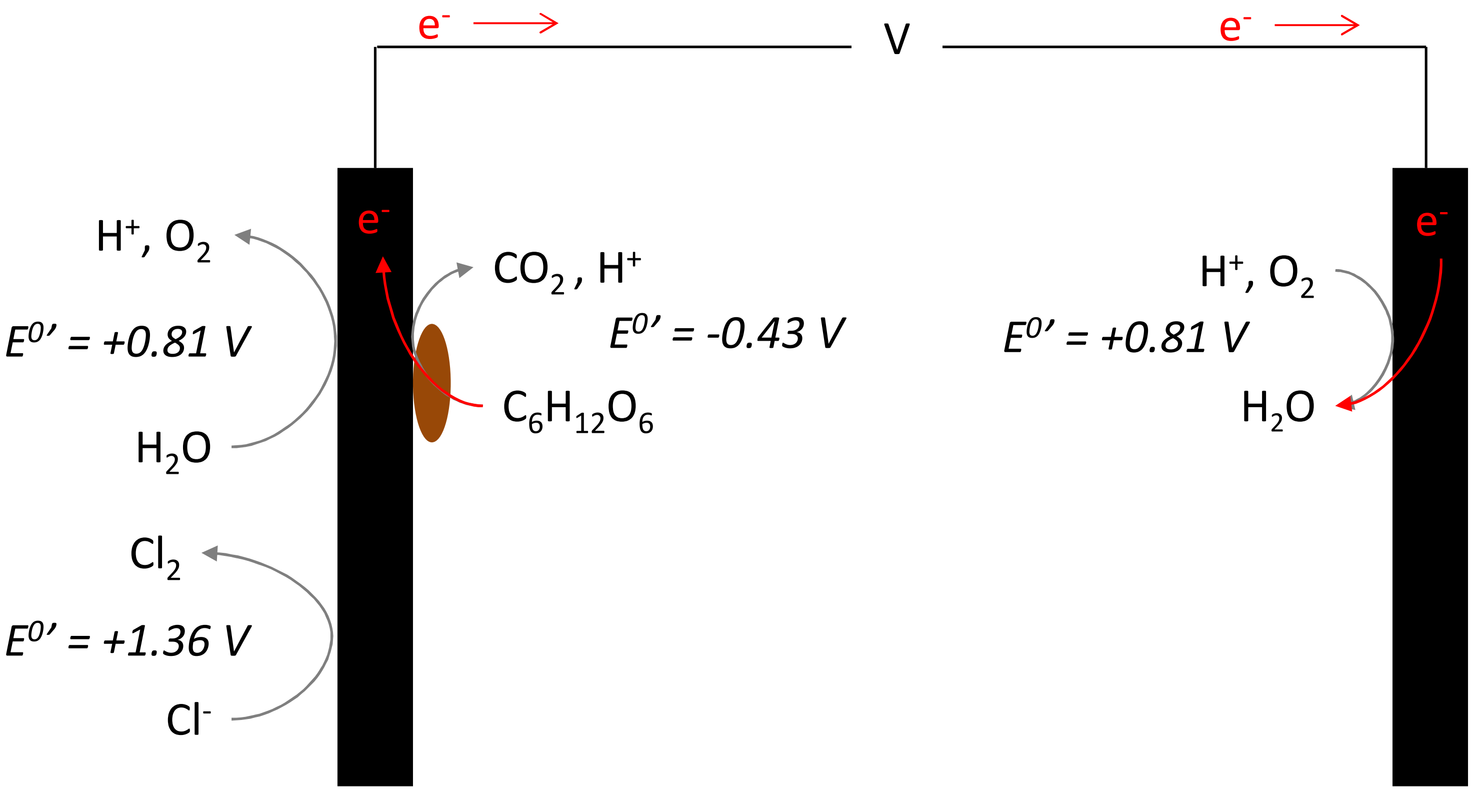
Before we start…

- **Catalysts facilitate reactions by lowering the activation energy**



Why do we want microbes on electrodes?

Catalyzing complex reactions



1. Microbes can catalyze complex reactions
2. Microbes are self-generating and inexpensive

How do microbes accomplish extracellular electron transfer?

Direct contact

E.g. Geobacter sulfurreducens produce electrically conductive pili

See:

Lovley, 2006. Bug juice: harvesting electricity with microorganisms. Nature Microbiology 4, 497-508.
Reguera et al. 2005, Extracellular electron transfer via microbial nanowires. Nature 435, 1098-1101.

Electron shuttles

E.g. Pseudomonas aeruginosa produces electron shuttles.

See:
Rabaey et al. 2005, Microbial phenazine production enhances electron transfer in biofuel cells. Environmental Science & Technology 39, 3401-3408.

Reactor design

What types of electrodes do we use?

- Graphite and carbon – relatively inexpensive, bacteria can attach

See e.g.

Logan et al. (2007). Graphite fiber brush anodes for increased power production in air-cathode microbial fuel cells. Environmental Science & Technology, 41, 3341-3346.

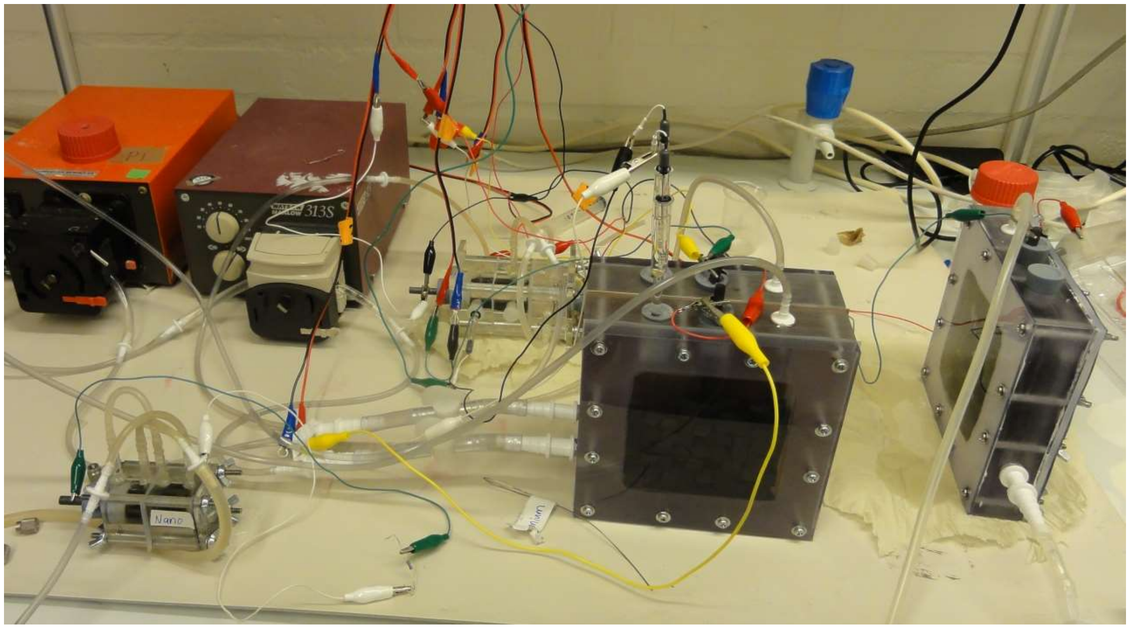
Saheb-Alam et al. (2018). Effect of Start-Up Strategies and Electrode Materials on Carbon Dioxide Reduction on Biocathodes. Applied and Environmental Microbiology, 84(4), e02242-17.

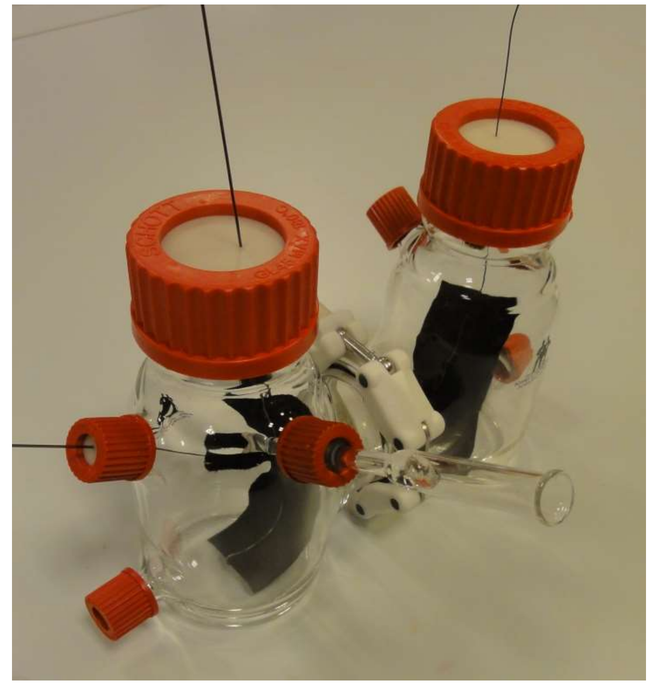
High *i* electrodes

- Porous carbon fiber electrode produced by gas-assisted electrospinning
- 30 A/m^2

See e.g.
Chen et al. (2011). Electrospun and solution-blown three-dimensional carbon fiber nonwovens for application as electrodes in microbial fuel cells. Energy & Environmental Science 4, 1417-1421.

Reactors





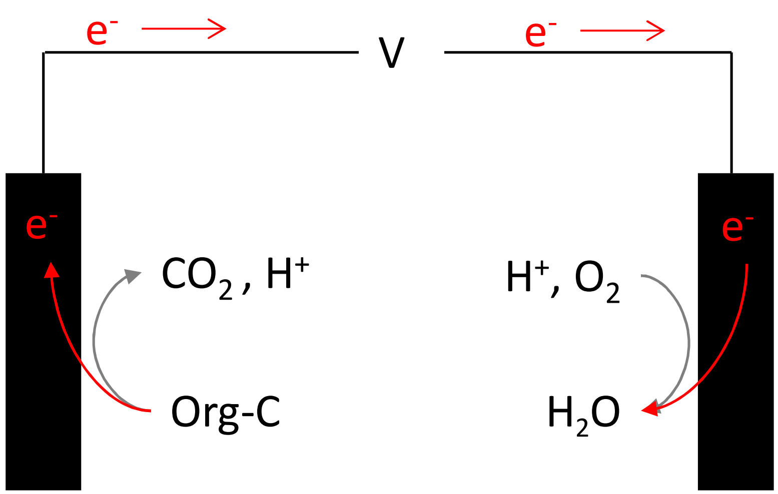
Applications

Types of microbial electrochemical cells

- Microbial fuel cell: galvanic cell, used to produce electrical power
- Microbial electrolysis cell: electrolytic cell, used to produce/recover a product

- Microbial desalination/electrodialysis cells: used to move ions between compartments

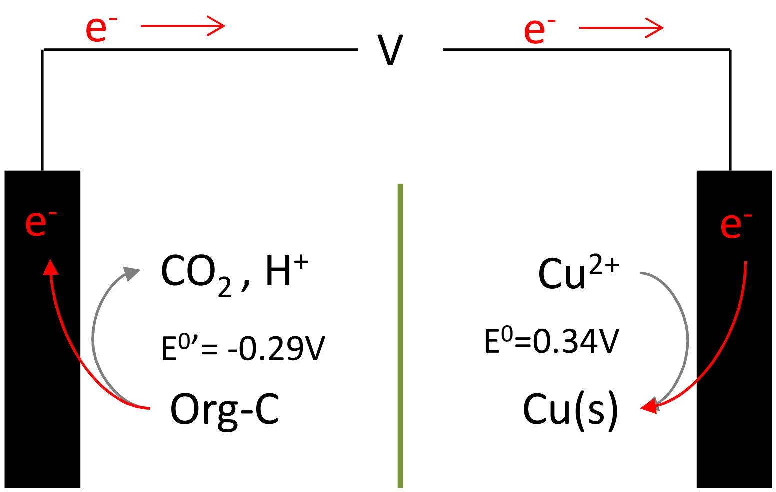
Microbial fuel cell



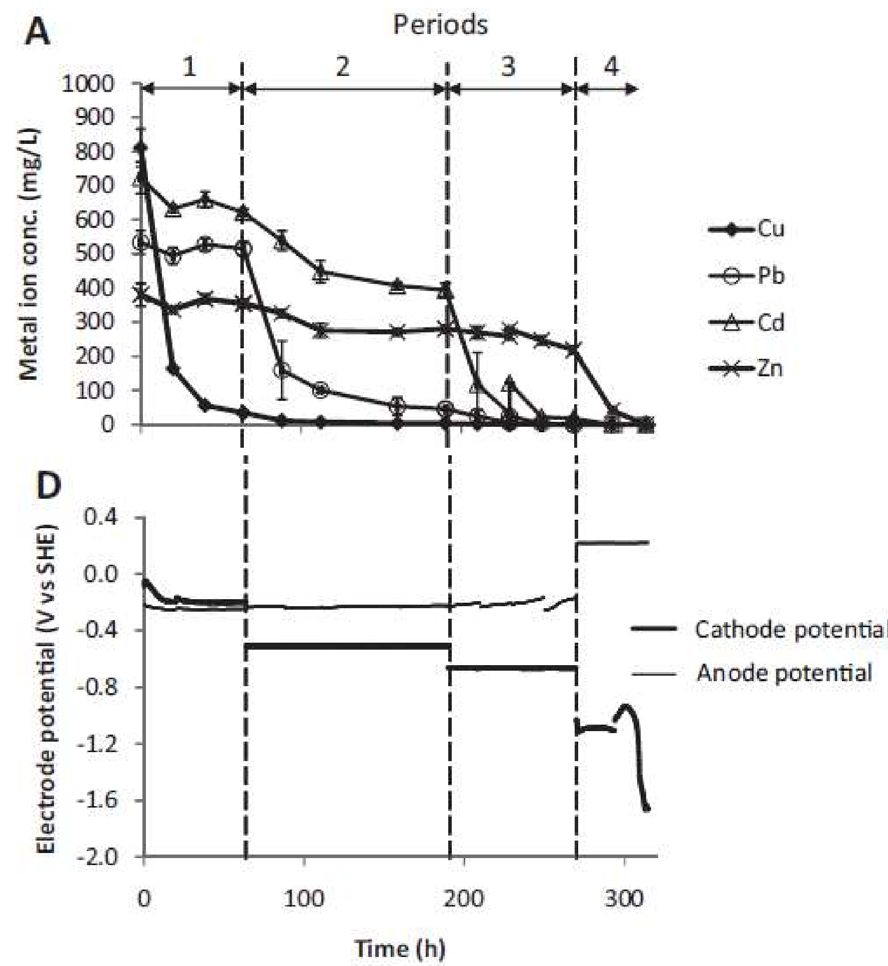
4.3 W/m^2 at 16.4 A/m^2
2.87 kW/m^3 at 10.9 kA/m^3

See:
Fan et al. (2012). Improved performance of CEA microbial fuel cells with increased reactor size. Energy & Environmental Science, 5, 8273-8220.

Microbial fuel/electrolysis cell for metal recovery



See:
Ter Heijne et al. 2010. Environmental Science & Technology 44(11), 4376-4381.



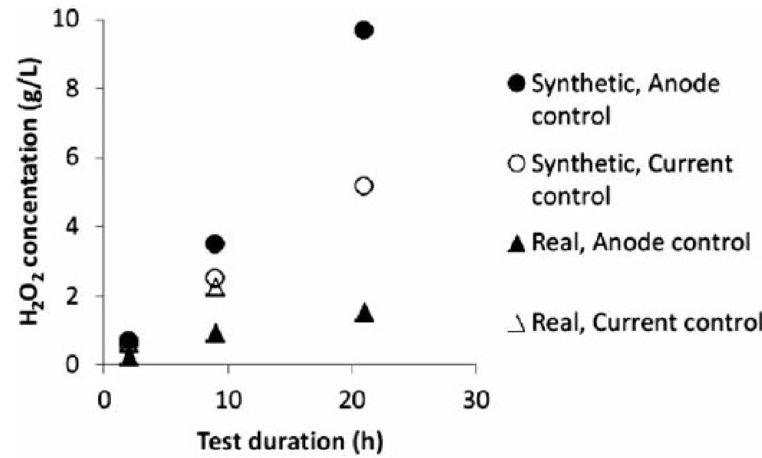
Modin et al. 2012. Journal of Hazardous Materials 235-236, 291-297.

Microbial electrolysis cell for hydrogen production

See e.g.
Liu et al. 2005. Environmental Science & Technology 39, 4317-4320.
Rozendal et al. 2006. International Journal of Hydrogen Energy 31, 1632-1640.

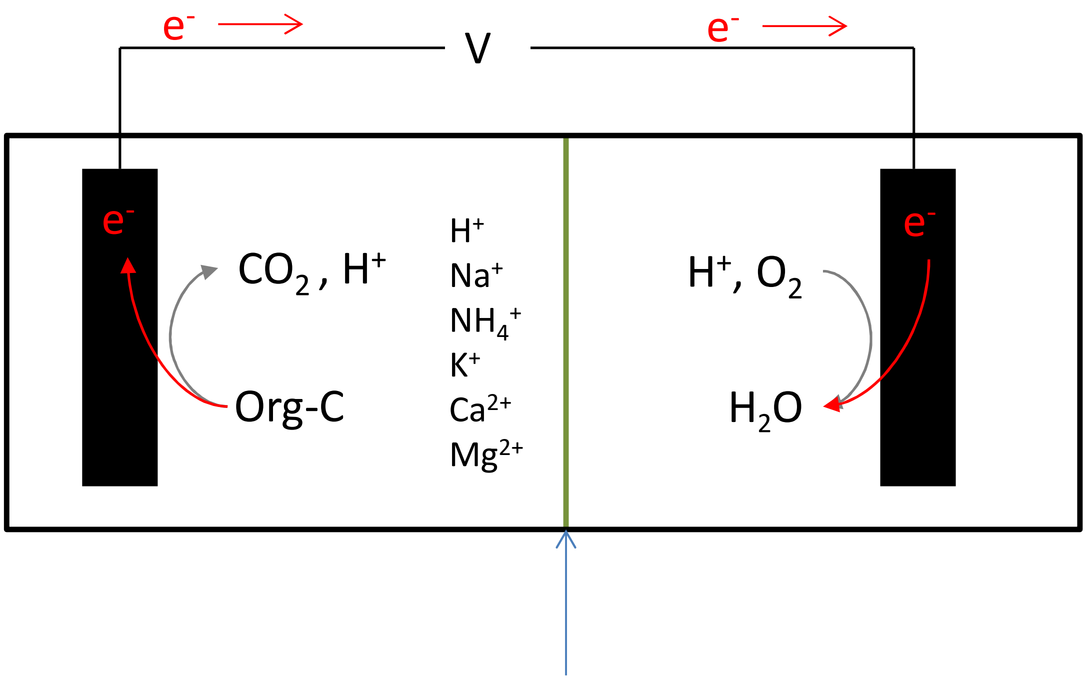
Microbial fuel/electrolysis cell for H_2O_2

See e.g.
Rozendal et al. 2009. Electrochemistry Communications 11, 1752-1755.



Modin & Fukushi 2012. Environmental Technology 34(19) 2737-2742.

Microbial electrolysis cell for caustic



Cation exchange membrane
Rozendal et al. 2006, Environmental Science & Technology 40, 5206-5211.

A mixed caustic is generated in the cathode chamber.
3.4% (wt) produced by Rabaey et al. Environmental Science & Technology 44, 4315-4321.

Microbial desalination cell

See
Cao et al. 2009. Environmental Science & Technology 43, 7148-7152
Chen et al. 2011. Environmental Science & Technology 45, 2465-2470

Microbial reverse electrodialysis cell

Energy can be harvested when salt water mixes with fresh water.

See
Kim and Logan 2011, PNAS 108(39), 16176-81.
Kim and Logan 2011, Environmental Science & Technology 45, 5834-5839.

Ammonium treatment

- Using the alkalinity increase at the cathode to support nitrification (Modin et al. 2011. Water Research 45, 2691-2699.
- Concentrate NH_4^+ at the cathode by migration from the anode compartment (Kuntke et al. 2011, Bioresource Technology 102, 4376-4382)
- Volatilize and capture NH_3 at the cathode (Wu and Modin 2013, Bioresource Technology 146, 530-536)

Sensors

See
Kim et al. (2003). Biotechnology Letters 25, 541-545.
Stein et al. (2010). Bioelectrochemistry 78, 87-91

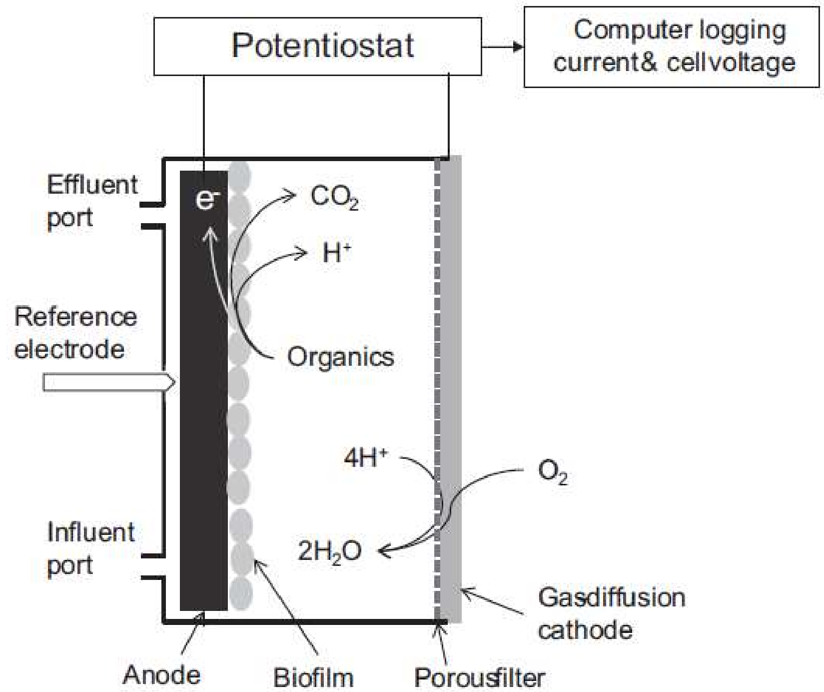


Fig. 1 – Schematic of bioelectrochemical reactor used as BOD sensor.

Modin & Wilén (2012). Water Research 46, 6113-6120.

MFC powered by plants

http://www.bioenergie-promotion.fr/10911/le-projet-plantpower-piles-a-combustibles-alimentees-par-des-plantes/

Gastrobots / Ecobots
Robots powered by MFCs

Melhuish et al. 2006. Auton Robots 21, 187-198

http://thedailyomnivore.net/2011/02/21/gastrobot/

Biological cathodes

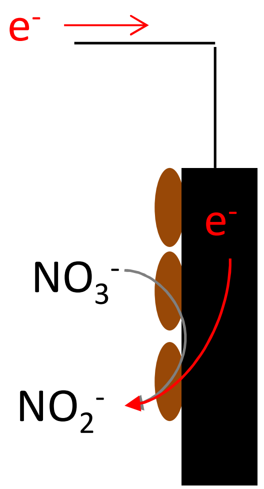
- Oxygen reduction
- Denitrification
- Hydrogen production
- Methanogenesis
- Acetogenesis
- Ethanol production
- Caproate
- 1,3 propanediol

O_2 reduction

Rabaey et al. 2008. (The ISME Journal 1-9) identified some bacteria on a O_2 reducing cathode as *Sphingobacterium*, *Acinetobacterium* and *Acidovorax* sp.

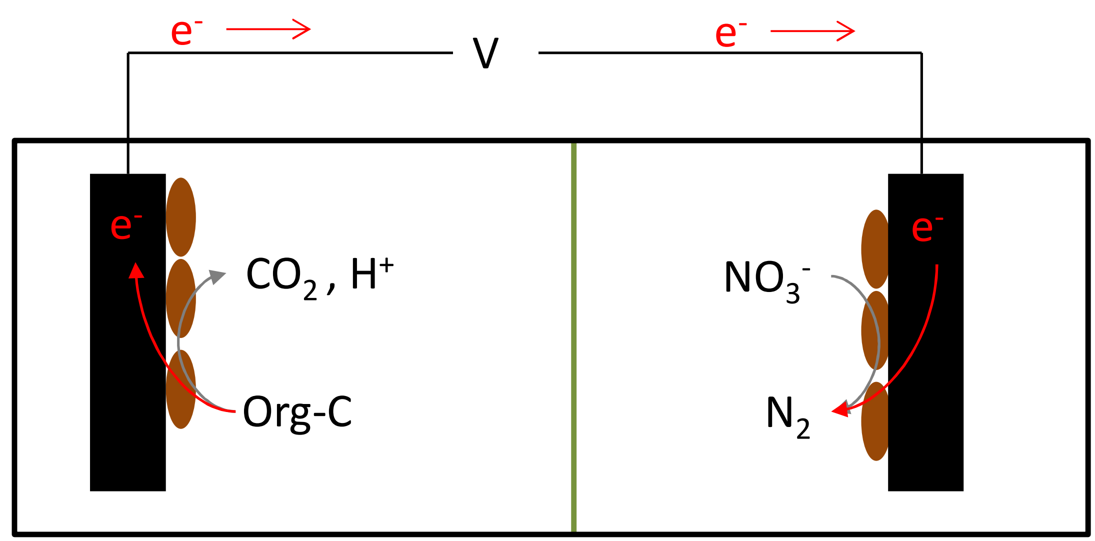
Bergel et al. 2005. Electrochemistry Communications 7, 900-904.

Denitrification



Gregory et al. 2004. Environmental Microbiology 6(6), 596-604.

Geobacter can reduce nitrate to nitrite.



Clauwaert et al 2007. Environmental Science & Technology 41, 3354-3360.

Nitrate can be used as electron acceptor in microbial fuel cell.

Hydrogen production

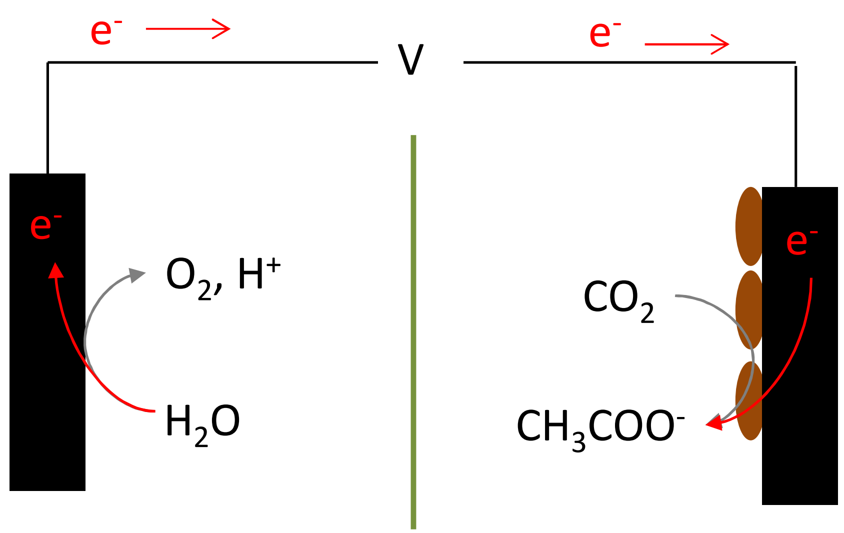
See
Rozendal et al. 2008. Environmental Science & Technology 42(2), 629-634.

Methanogenesis

Methanobacterium palustre dominated a biocathode that produced methane

Cheng et al. 2009. Environmental Science & Technology 43, 4953-4958.

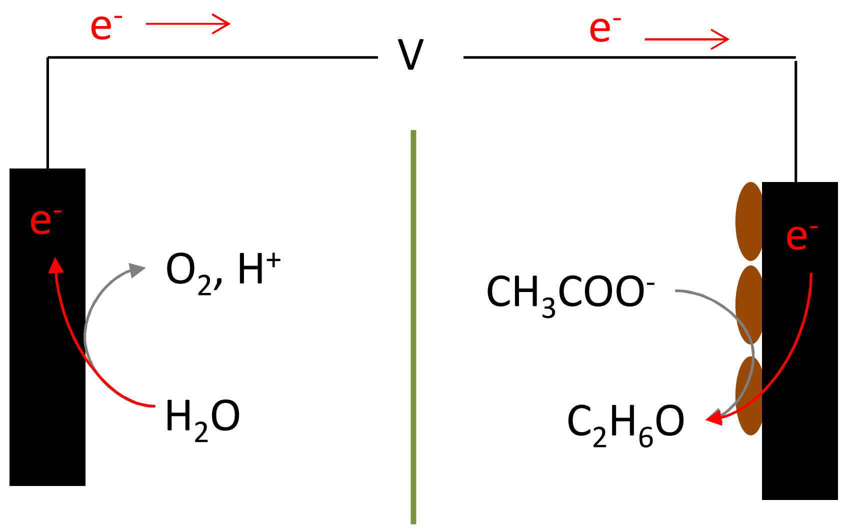
Acetogenesis – microbial electrosynthesis



Nevin et al. 2010. mBio 1(2), e00103-10.

Sporomusa ovata can reduce CO_2 to acetate on an electrode

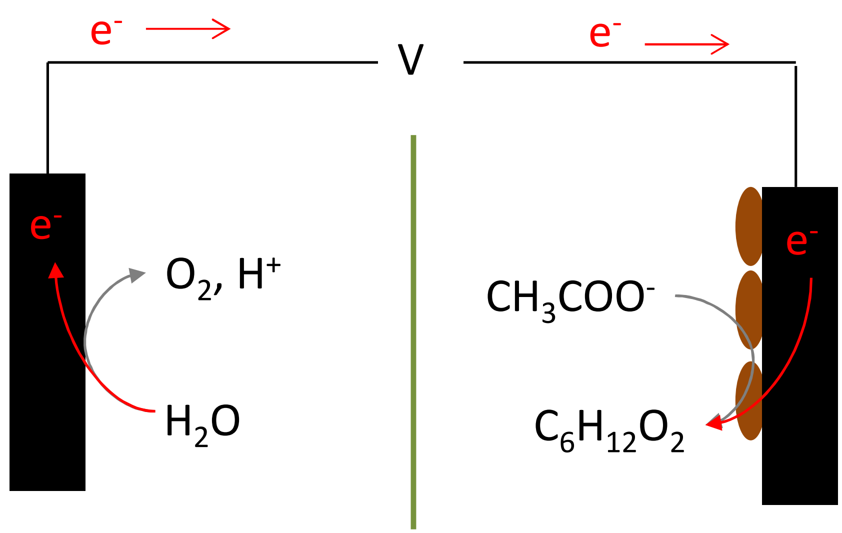
Ethanol production



Steinbusch et al. 2010. Environmental Science & Technology 44, 513-517.

Used methyl viologen as an electron shuttle to reduce acetate to ethanol.

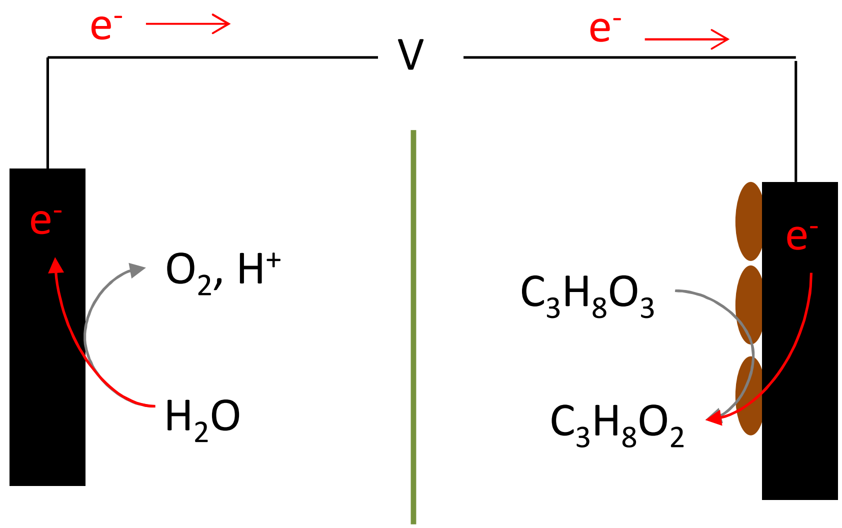
Caproate production



Jansen et al. 2013. ACS Sustainble Chemistry Engineering 1(5), 513-518.

Reduced acetate to caproate at cathode poised at -0.9 V.

1,3-propanediol production



Zhou et al. 2013. Environmental Science & Technology 47, 11199-11205.

Reduced glycerol to 1,3-propanediol at cathode poised at -0.9 V.

History of microbial electrochemical technologies

- 1911 – *emf* coupled to the biological degradation of organic substances discovered (Potter MC, 1911. Proc Roy Soc Lond B 84:260–276)
- 1960s – NASA investigates MFCs for space flights
- 1980s, 1990s – work on MFCs using redox shuttles
- 2001: Byung-Hong Kim et al. patents a microbial fuel cell without electron shuttles and with wastewater as fuel.

History is described by Schröder 2011, Discover the possibilities: microbial bioelectrochemical systems and the revival of a 100-year-old discovery, Journal of Solid State Electrochemistry 15, 1481-1486.