Electricity Directly from Wastewater – an Overview of the New Field of Electromicrobiology

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Acknowledgements

- Li, B., Scheible, Curtis, M. (2011) Electricity Generation from Anaerobic Wastewater Treatment in Microbial Fuel Cells, *WERF Report*
- Logan, B.E., Zuo, Y. (2008) New Electrode Material for Microbial Fuel Cells …, *WEFTEC*
- Franks, A. (2012) What's Current with Electric Microbes?, *J Bacteriol Parasitol*
- Lovely, D.R. (2012) Electromicrobiology, *Annu. Rev. Microbiology*
- Xie, X. et al. (2013) Microbial battery for efficient energy recovery, *PNAS*

Electromicrobiology

- New field of interdisciplinary microbiology dealing with microbes capable of interacting with insoluble electron acceptors/donors (electrodes)
- “Electric” bacteria are capable of transferring electrons extracellularly from solid surfaces. This drives internal metabolic processes
- Present in Nature for eons, only recently more sensitive sensors allow in-depth study

Energy

- Source of most of energy in human endeavors is burning of fossil fuels

Energy from Fossil Fuels

C (organic carbon) + O_2 → CO_2 + energy

- Oxygen serves here as electron acceptor (gets reduced from 0 to -2), in a reaction that releases heat

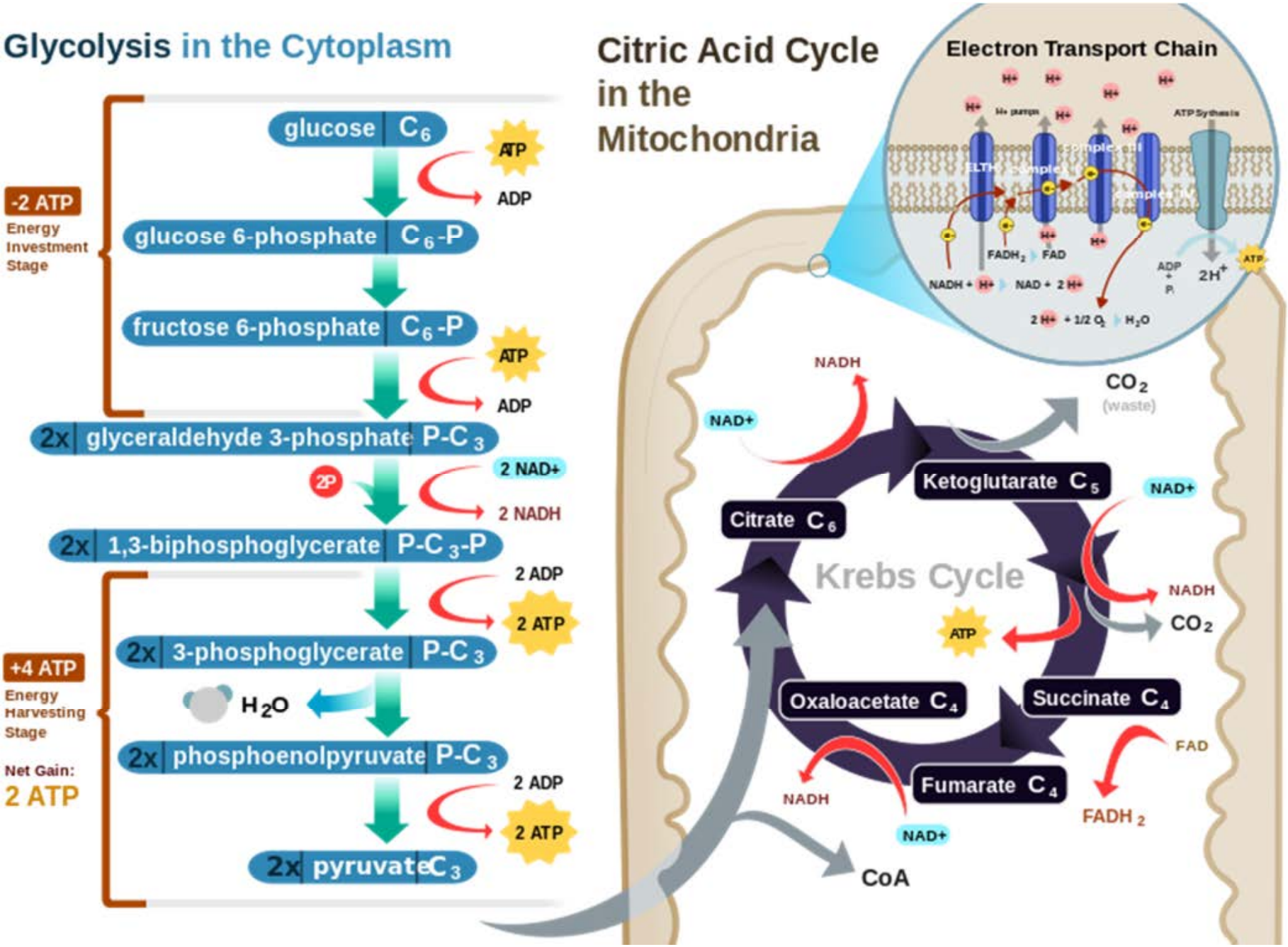
- Photosynthesis – green plants utilize sun's energy for loading carbon in CO_2 with electrons stripped from O^{-2} in CO_2 and releasing O_2; that now combustible (organic) carbon is converted into biomass – future fuel

Respiration

- Respiration - a familiar way of life for almost all organisms in animal kingdom (including bacteria)
  - As in a fuel burning, Oxygen is used as electron acceptor with CO_2 being end product. It is just done at a controlled pace, at low temperatures
  - Heterotrophic (“normal”) and nitrifying bacteria do it in aerobic activated sludge utilizing O_2
  - Other electron acceptors are used in anoxic zone (NO_3^-) and in anaerobic processes (SO_4^{-2}, ammonia, organic compounds)

Respiration

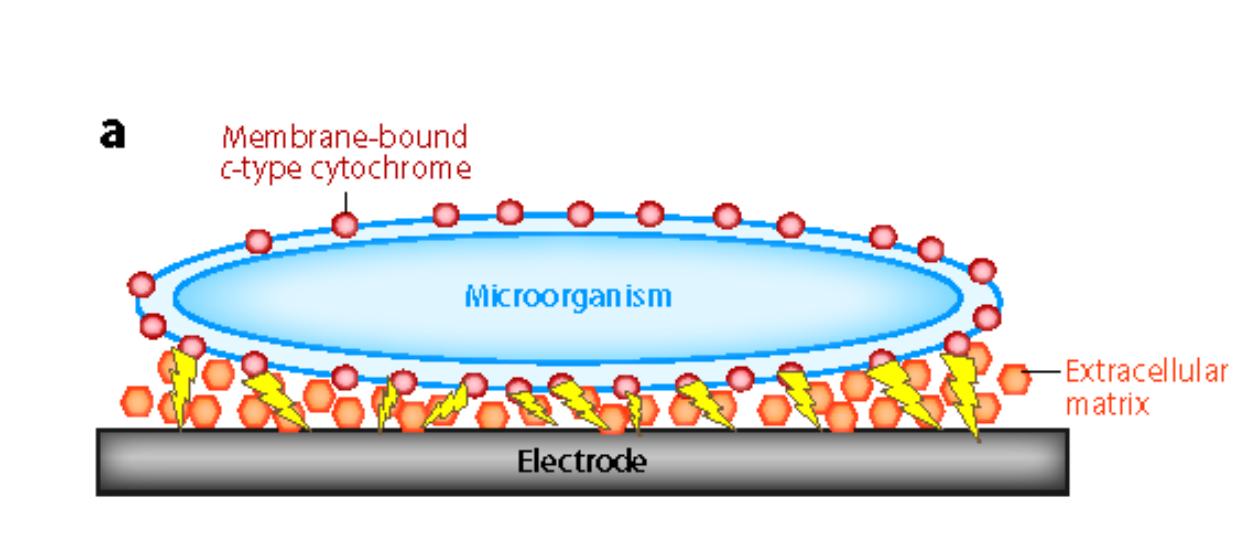
- In “normal” bacterial respiration the key process of electron transfer to electron acceptor (molecular oxygen) happens by diffusion of Oxygen to cell or cell wall
- A cascade of chemical reactions takes than place inside the cell and through molecular exchanges through the cell membrane


Glycolysis in the Cytoplasm
glucose C6
ATP
ADP
-2 ATP
Energy Investment Stage
glucose 6-phosphate C6-P
fructose 6-phosphate C6-P
ATP
ADP
2x glyceraldehyde 3-phosphate P-C3
2P
2 NAD+
2 NADH
2x 1,3-biphosphoglycerate P-C3-P
2 ADP
2 ATP
2x 3-phosphoglycerate P-C3
H2O
2x phosphoenolpyruvate P-C3
2 ADP
2 ATP
2x pyruvate C3
+4 ATP
Energy Harvesting Stage
Net Gain:
2 ATP
Citric Acid Cycle in the Mitochondria
Electron Transport Chain
H+
ATP Synthesis
FADH2
FAD
NADH + H+
NAD + 2 H+
2 H+ + 1/2 O2
H2O
ADP + Pi
2H+
ATP
NADH
CO2
(waste)
NAD+
Ketoglutarate C5
Citrate C6
Krebs Cycle
NADH
CO2
ATP
Oxaloacetate C4
Succinate C4
FAD
FADH2
Fumarate C4
NADH
NAD+
CoA

Key Discovery

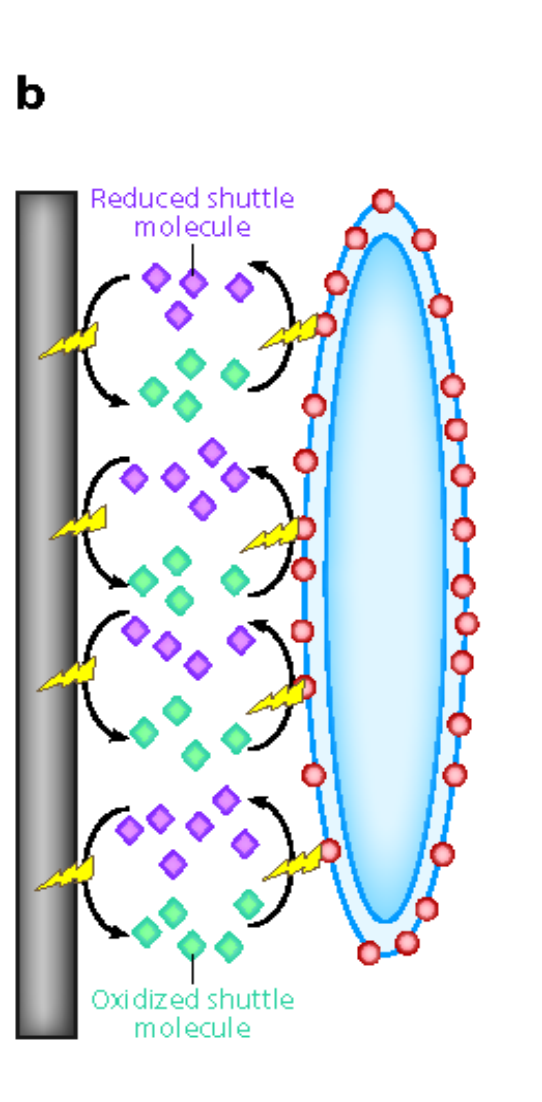
- Some microorganisms are capable of oxidizing organic compounds with direct electron transfer to electrodes
- In other words, oxygen (or other electron acceptor, such as NO_3^-, SO_4^{-2}, other organics) does not need to migrate inside the cell or be at the cell wall

Mechanisms of Electron Transfer by Bacteria to Electrode



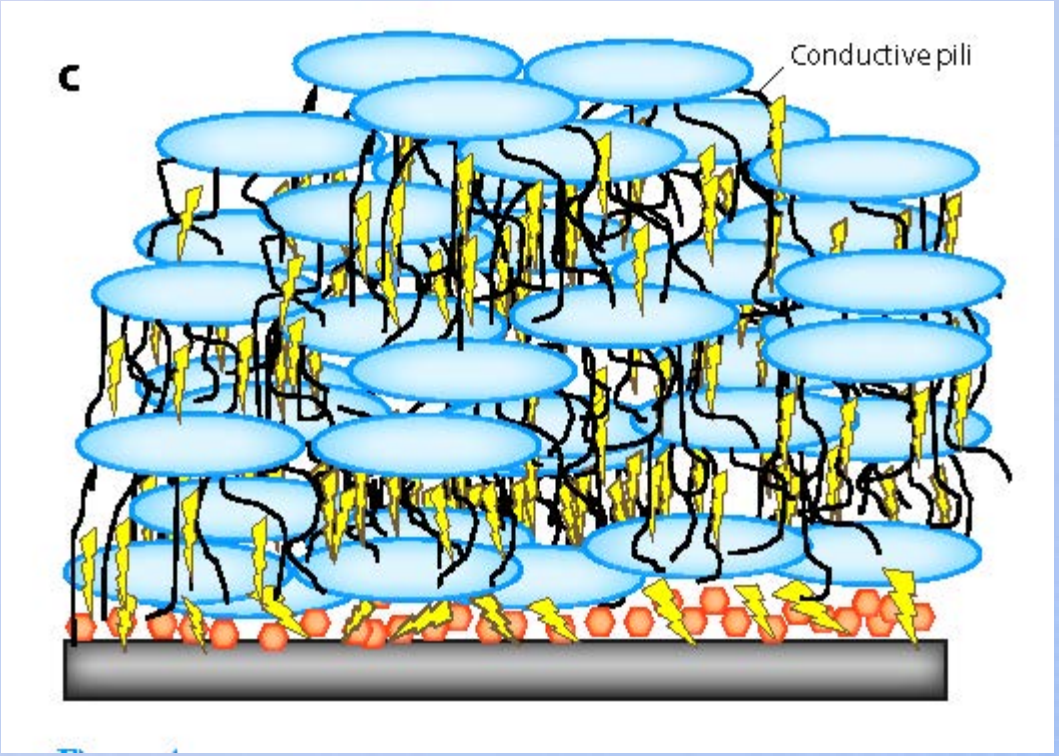
- Short-range electron transfer through redox active proteins such as c-type cytochromes (associated with outer cell surface)

Mechanisms of Electron Transfer by Bacteria to Electrode



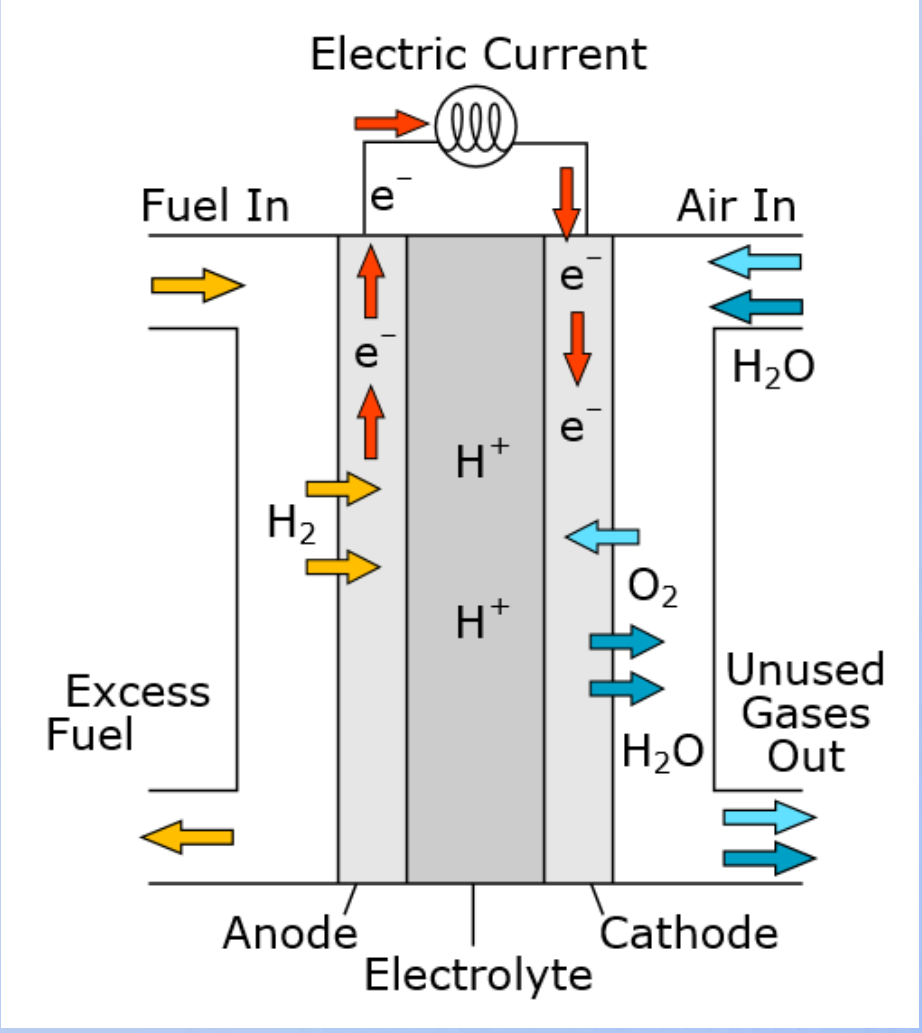
- Transfer by reduction of soluble electron shuttle molecules released by bacteria

Mechanisms of Electron Transfer by Bacteria to Electrode



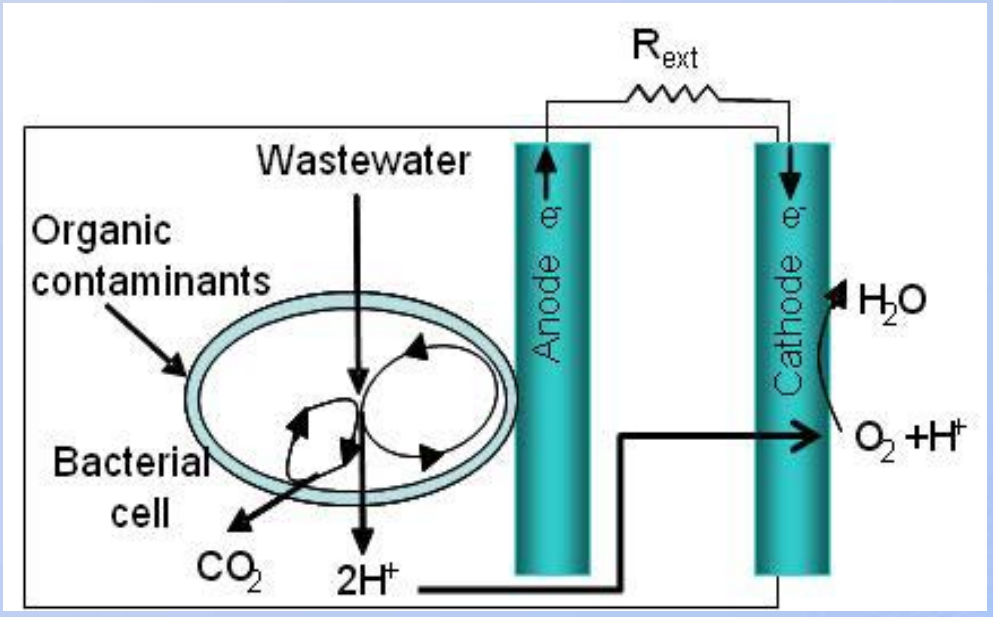
- Long-range transfer through pili – a conductive bilofilm with “nanowires”

Fuel Cell



- Converts fuel (hydrogen or hydrocarbons) directly to electricity
- Strips e^- from H_2
- Protons (H+) have to travel from anode to cathode through an electrolyte
- H_2O generated at cathode

Microbial Fuel Cell (MFC)



- Carbon anode accepts electrons from bacteria in biofilm
- Electrons react on cathode with oxygen and protons to form H_2O (catalyst needed)
- Hydrophobic membrane separates cathode from anode; allows flow of protons
- So oxygen remains separated from bacteria

MFC - Properties

- While COD removal from wastewater of up to 80% was reported, energetic efficiency in pilot size units is low
- Voltage is limiting, max. 0.6 V in the current design, so for usable conventional power stacking will be required
- …but there are other potential uses for low voltage power

MFC with Silver

- New designs use anode made of carbon cloth and cathode made of silver oxide
- As silver is toxic to bacteria, cathode is not fouled by bacteria
- As silver oxide is converted to silver, cathode needs to be regenerated (re-oxidized)
- 30% efficiency in extracting energy from wastewater shown in lab conditions

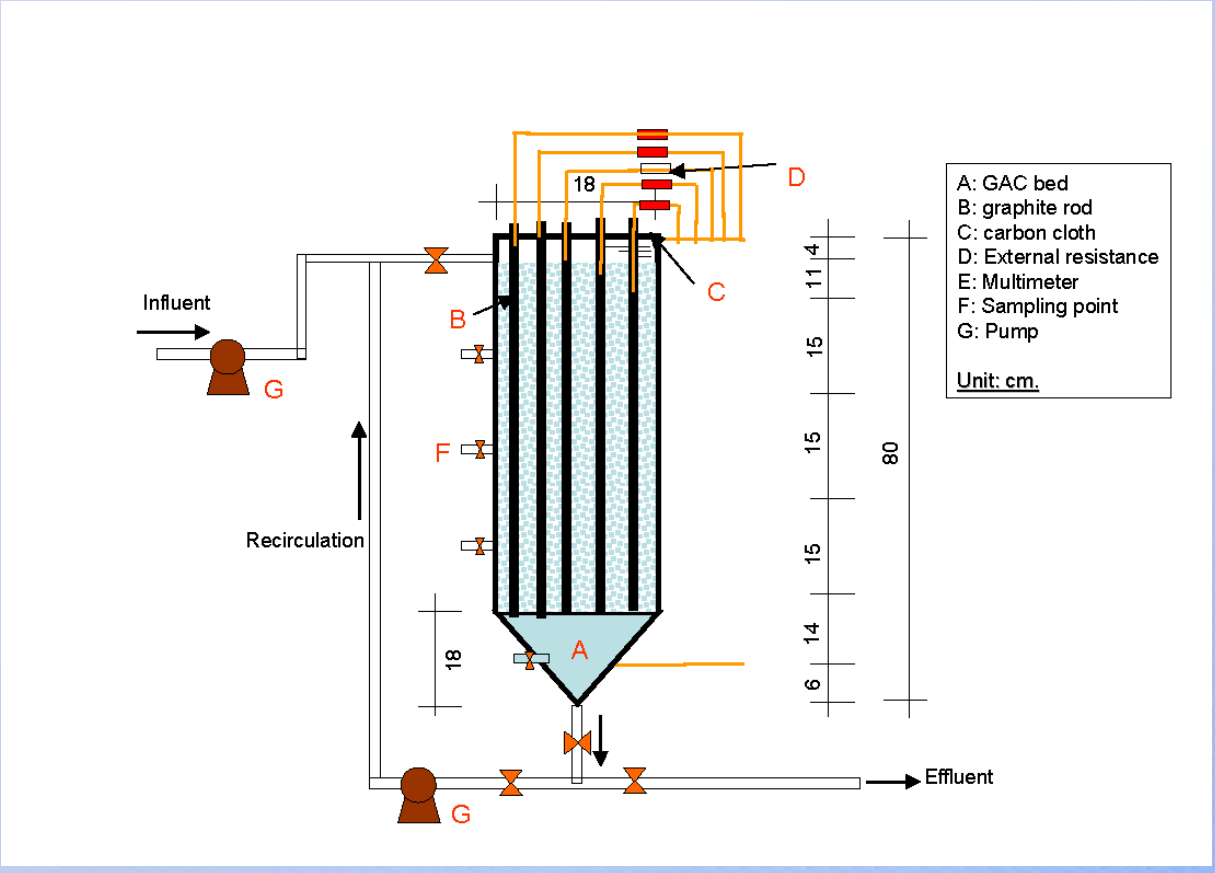
MFC – with Activated Carbon

- WERF- supported development of multi-anode/cathode granular activated carbon microbial fuel cell (MAC-GAC MFC)
- GAC used to support biofilm growth
- Multiple anode/cathode allow higher power density
- 80% COD removal (real ww)
- Cheaper catalyst MnO_2 vs platinium

MFC – with Activated Carbon

- After acclimation, HRT of 10 hrs required
- GAC bed is a anode, where electrons discharged by bacteria are accepted
- Carbon cloth is anode, where electrons are accepted by oxygen and combine with protons to form water
- The process of electrons discharged from the cathode (oxygen) requires catalyst to speed it up

MFC with GAC and carbon electrodes



Commercialization

- Pilus Energy – GalvaniBot with GeRM keys to prevent theft of technology
- Through Tauriga Sciences they launched this year pilot at Metropolitan Sewer District of Greater Cincinnati
- EcoVolt – claims to utilize MFC to mediate anaerobic treatment of high strength wastewater

Problems to overcome

- So far only filtered primary effluent tested
- Low voltage generated (<1 V) will require stacking
- Low power density
- Difficulties in scaling-up

Other Potential MFC Applications

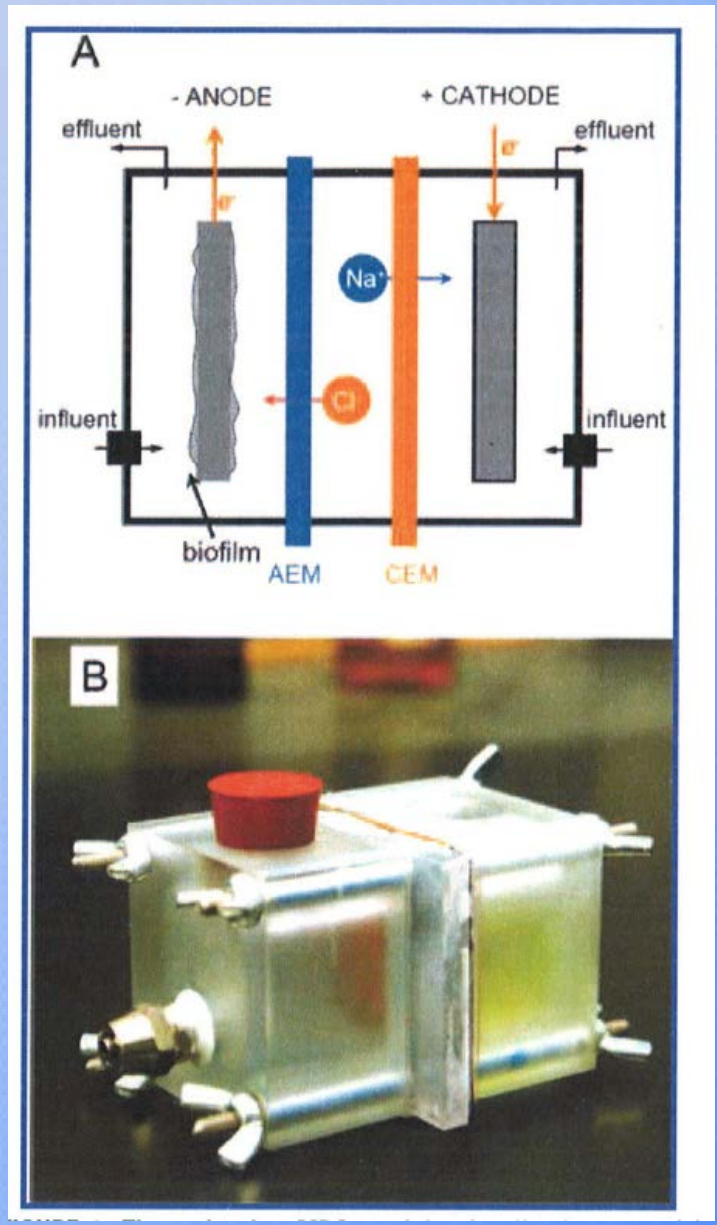
- As sensors for microbial activity
- Powering of low power devices in aquatic environment
- Desalination w/o electricity
- Stimulating bioremediation
- Balancing electron flow during production of commodity chemicals
- Corrosion (transfer of electrons from metals) inhibition

Reverse Microbial Fuel Cell

- Some microbes could actually reverse the situation and accept electrons from an electrode
- Being able to provide energy to microbes directly through an electrode has significant potential for bioremediation of recalcitrant contaminants, such as chlorinated compounds
- Another area is electrosynthesis – fixation of CO_2 by microbes utilizing the reducing power of an electrode

Microbial Desalination Cell (MDC)

- Potential for sustainable desalination off grid, potentially in conjunction with wastewater treatment and power generation!

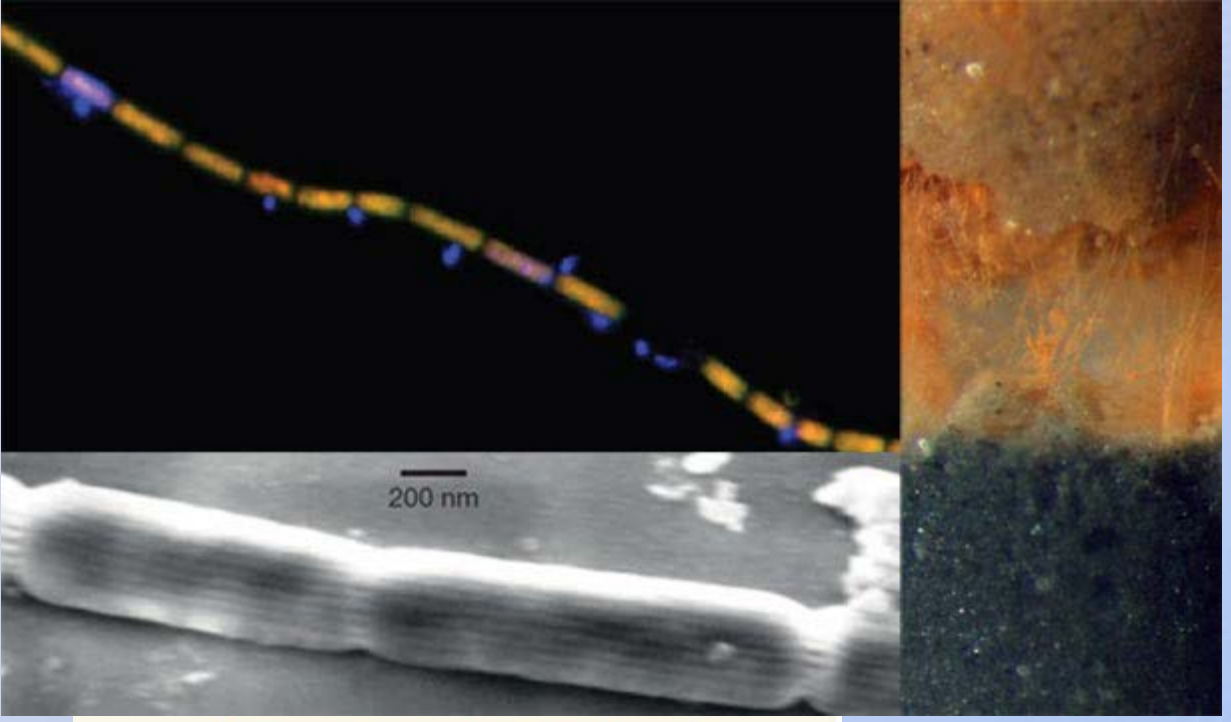


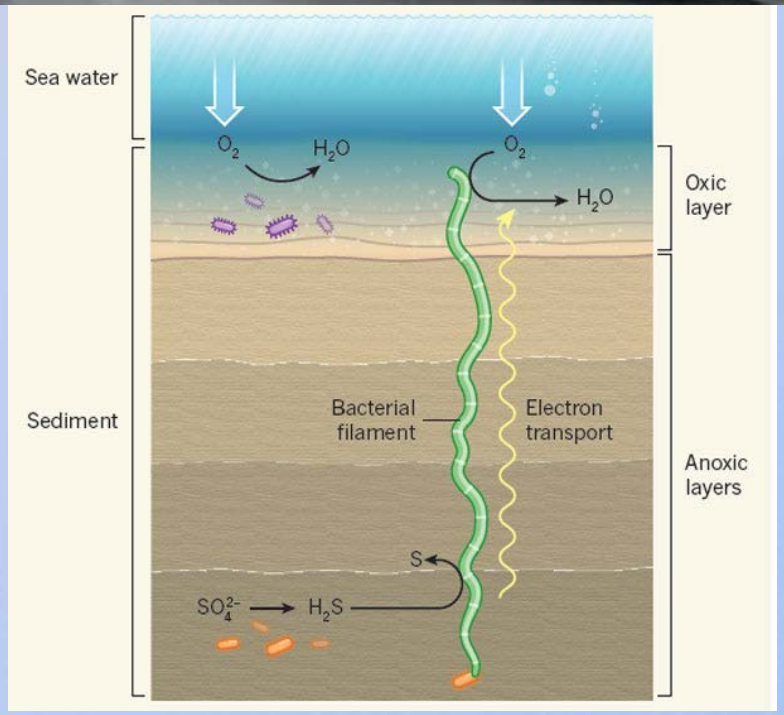
MEDIC Microbial Electro De-Ionization Cell

- Current research includes addition of ion-exchange resin to the cell (MEDIC) in a stacked configuration to improve cell conductivity for increased power density and improved desalination rates
- Comines MDC and EDI (electrodeionization)
- WEFTEC 2013 paper by Shehab, Logan *et al*
  - Initial NaCl solution de-ionized from 13 g/L to 200 mg/L
  - 75% COD removal

Geobacter metallireducenes

- Capable of oxidizing organic carbon to CO_2 while utilizing various metal oxides as electron acceptor
- Effectively it “breathes” metal; implications for bioremediation for heavy metals and radionuclides
- Can express flagella in a search for oxidized electron acceptor and use special cytochromes as capacitors





Geobacter sulfurreducens – unite into "cables" cm long nanowires (pili) to send electrons from SO_4^{2-} to surface for oxygen to take them

Electromicrobiology

- Rapidly emerging field of microbiology
- Better understanding of adaptations mastered for eons by microorganisms could soon lead to advancements in many fields, including related to wastewater:
  - Energy directly from organics in wastewater
  - Bacterial desalination
  - Bioremediaton