Rational Design of Electrodes in Electrochemical Energy Devices

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Electrochemical Devices

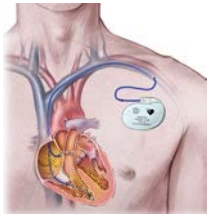
- Energy transfer and storage

Stationary power supply

Portable Electronics

Toys

Medical



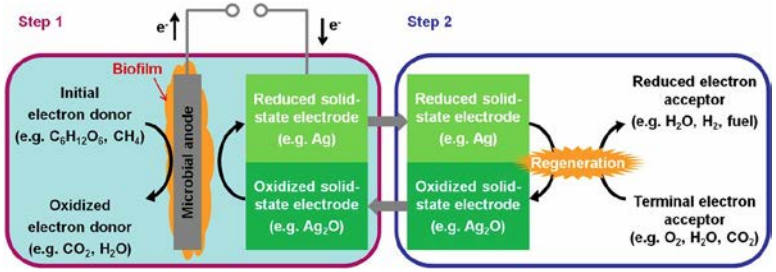
Vehicles

Grid-scale energy storage

Electrochemical Devices

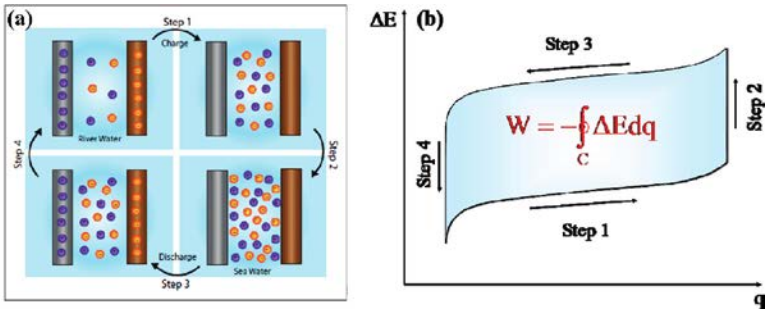
- Energy recovery

Waste organic matter



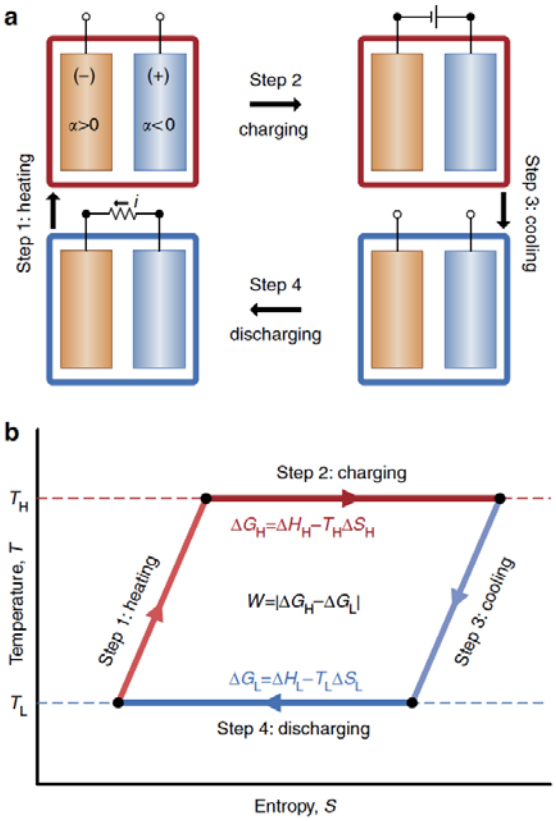
(X. Xie, et al. *PNAS.* 2013, 110: 15925-15930)

Salinity gradient



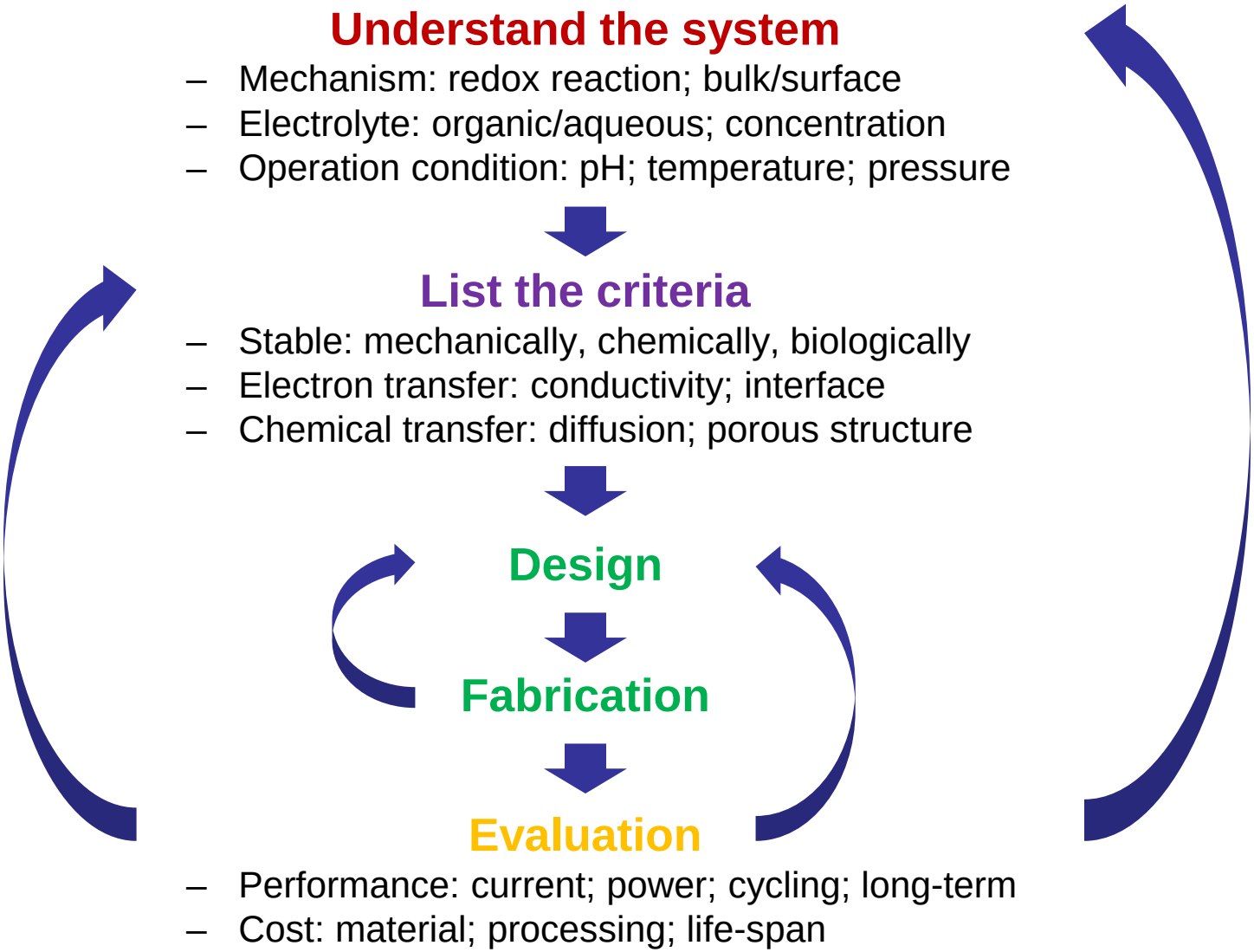
(F. Mantia, et al. *Nano Lett.* 2011, 11: 1810-1813)

Temperature gradient (waste heat)



(S. Lee, et al. *Nature Comm.* 2014, 5: 3942)

Rational Design of Electrodes: Roadmap



Example

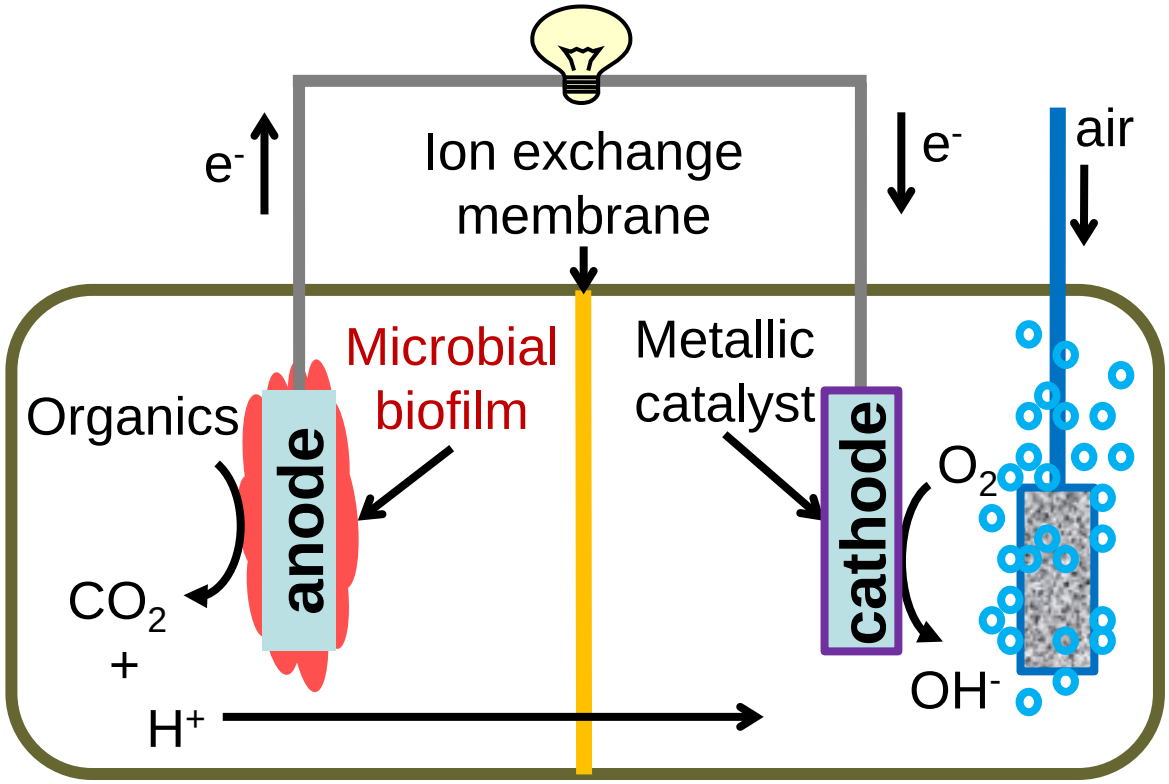
Design of Electrodes for Microbial Electrochemical Systems

References:

X. Xie, et al. *Nano Lett.* 2011, 11: 291-296
X. Xie, et al. Energy & Environ. Sci. 2012, 5: 5265-5270
X. Xie, et al. ACS Nano. 2014, 8: 11958-11965
X. Xie, et al. Energy & Environ. Sci. 2015: Advance Article

Microbial Electrochemical Systems

- **Energy: chemical → electricity**
- Microbial fuel cells

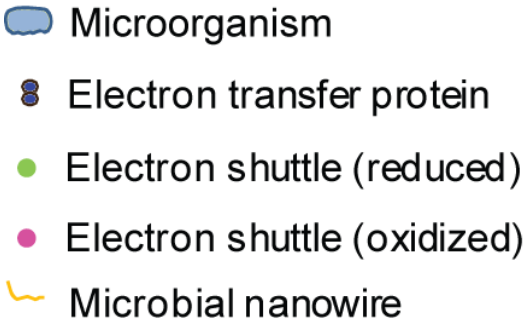


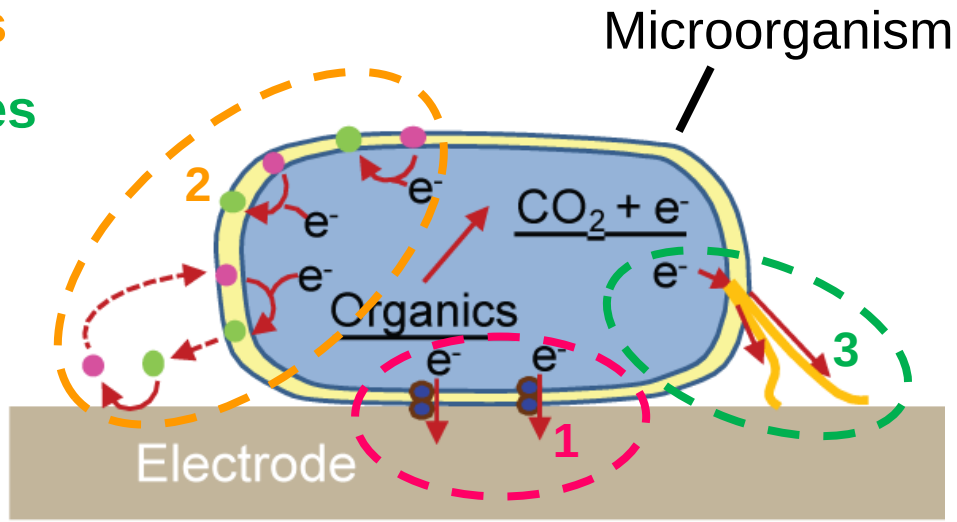
Bioelectrodes: Mechanism

- **Electrons: microorganisms → electrode**

Three pathways for extracellular electron transfer

1. **Direct membrane contact**
2. **Electron mediators**
3. **Microbial nanowires**





Living catalysts: 10-100 µm thick

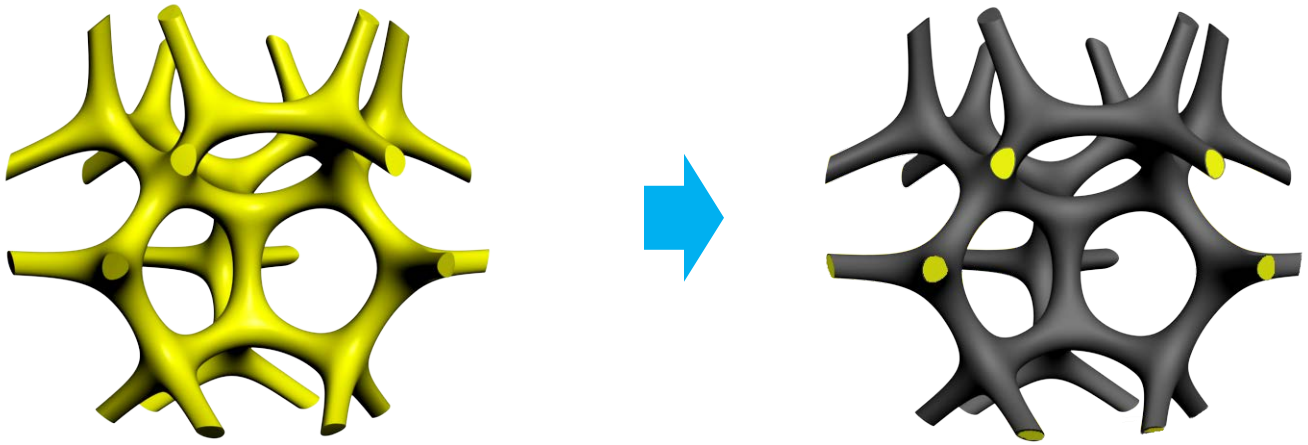
(Logan, *Nat Rev Microbiol*, 2009; Lovley, *Nat Rev Microbiol*, 2006)

Bioelectrodes: Criteria & Design

- **Conductive**
- **Stable (chemical & bio)**
- **Biocompatible**
- **Macroscale porous structure**
- **Affinitive electrode surface**

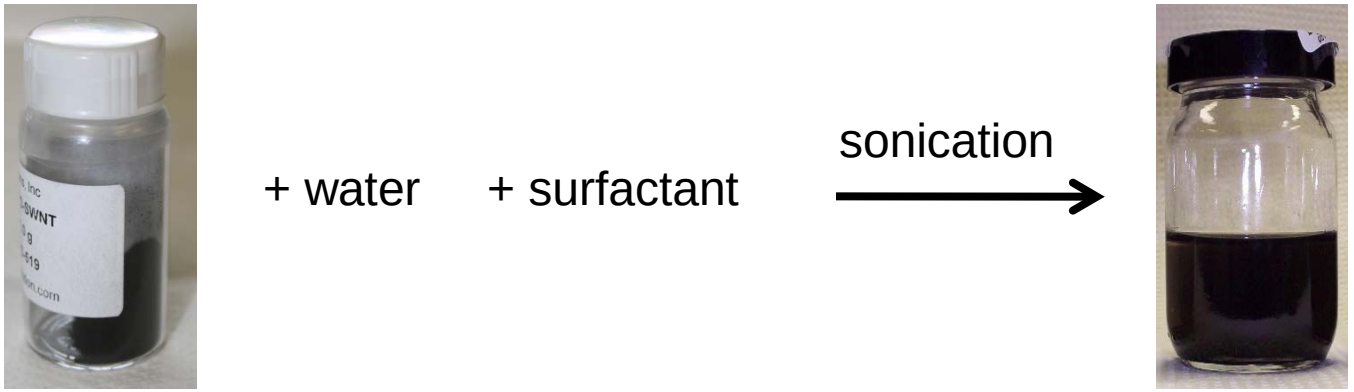
More microbes for electron transfer

More efficient electron transfer



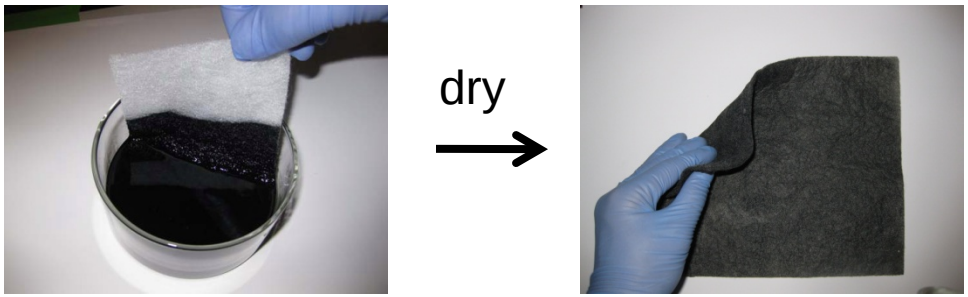
Carbon Nanotube (CNT)-Textile Synthesis

- **A simple and scalable process**



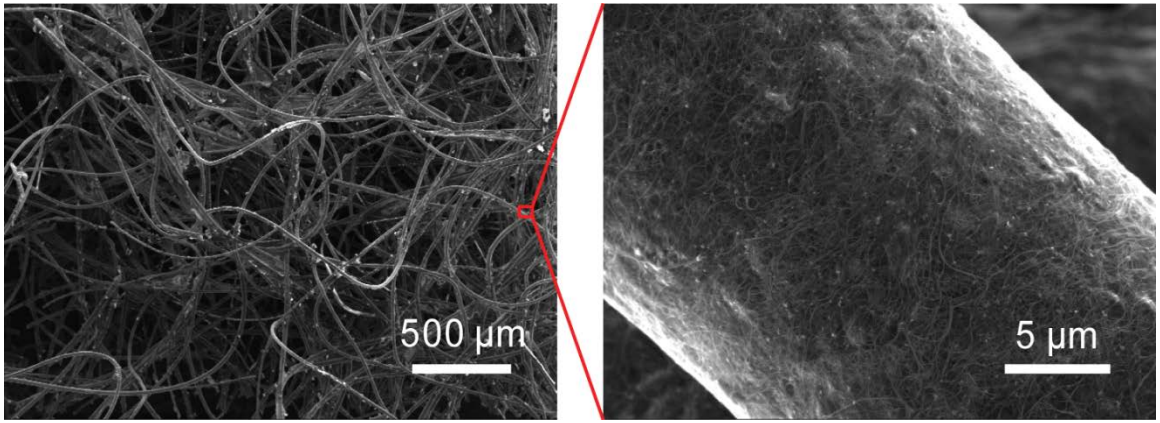
CNT powder

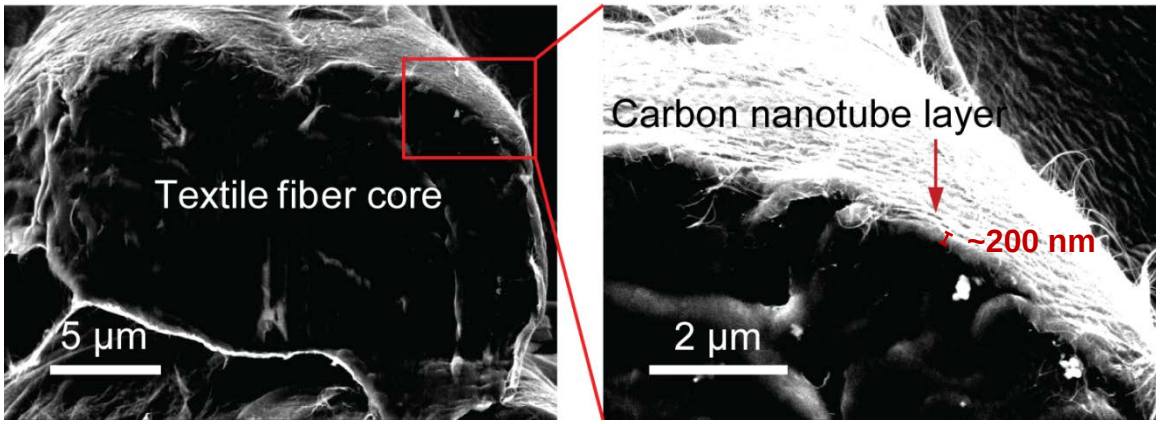
CNT ink



Hierarchical Structure of CNT-Textile

Macroscale porous textile

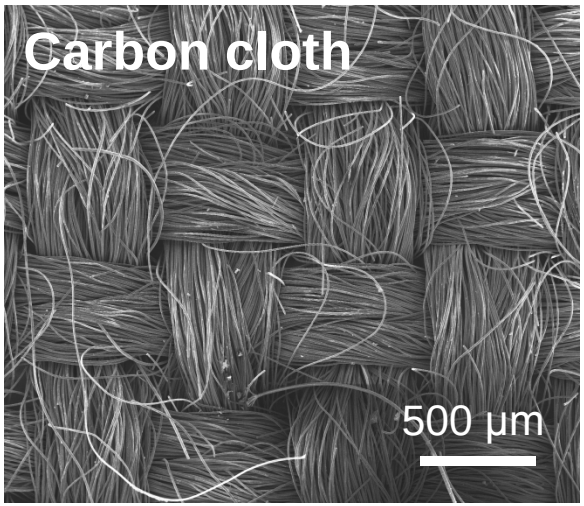




Microscale porous CNT coating

MFC Experimental Setup

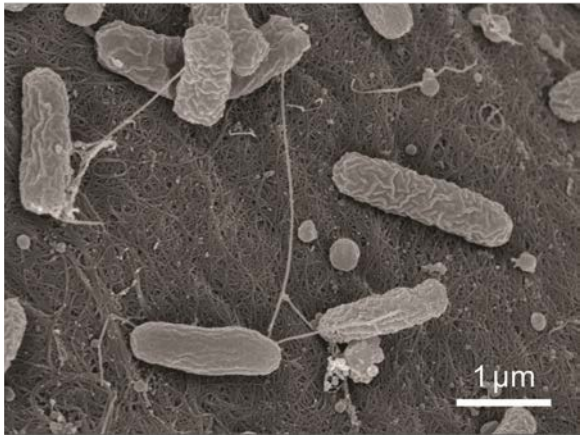
- H-shaped classic reactor
- Anode
  - **Carbon cloth** vs. **CNT-textile**
- Cathode
  - Pt on Carbon cloth
- Separator
  - Anion exchange membrane
- Feeding
  - Glucose (1 g/L)
- Inoculum (bacteria source)
  - Wastewater from Palo Alto Regional Water Quality Control Plant

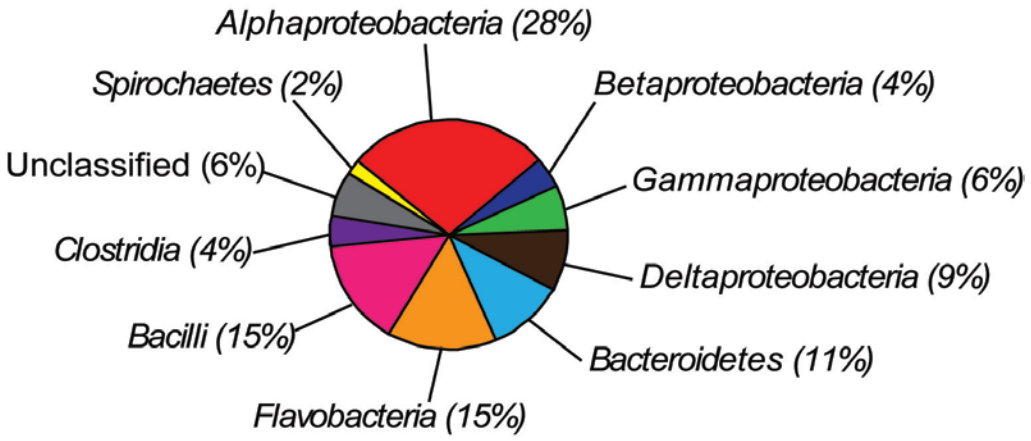


(X. Xie, et al. *Nano Lett.* 2011, 11: 291-296)

Biocompatibility

- Microorganisms on CNT-textile



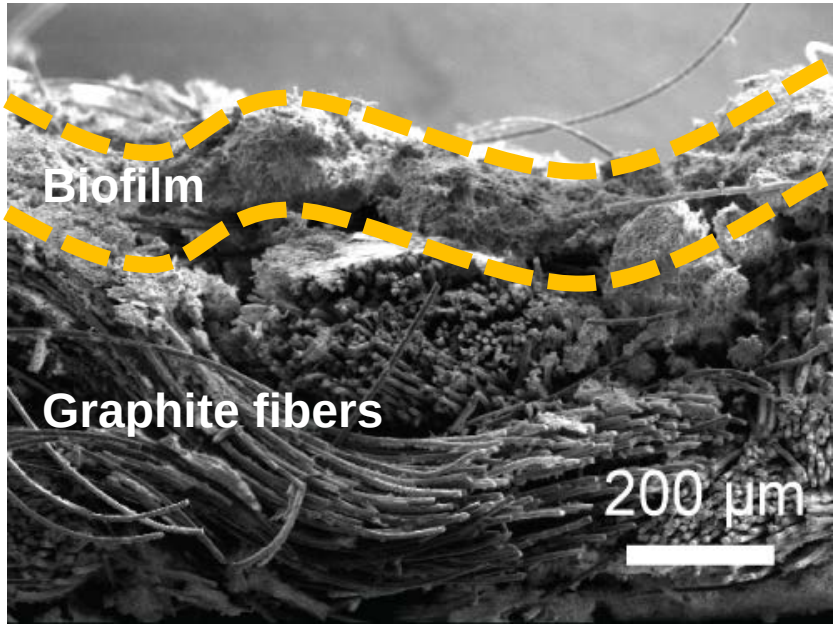


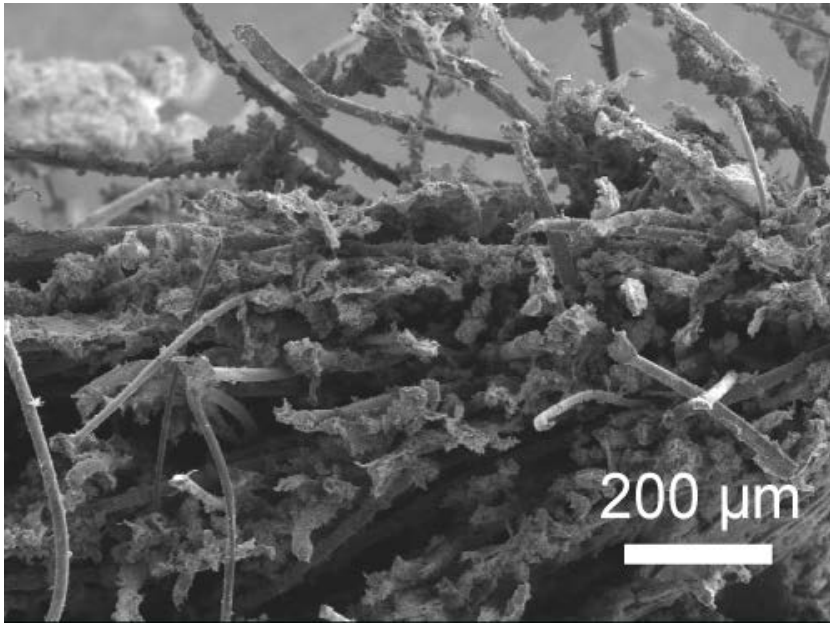
Evidence of colonization on CNT surface in MFCs

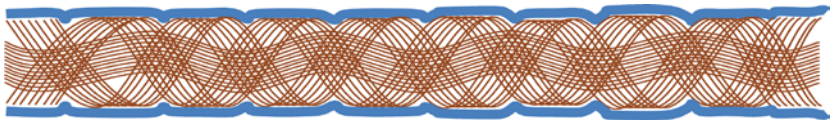
Macroscale Porous for Internal Colonization

- Cross-section of the anodes after 50 days of operation

Carbon cloth vs. **CNT-textile**



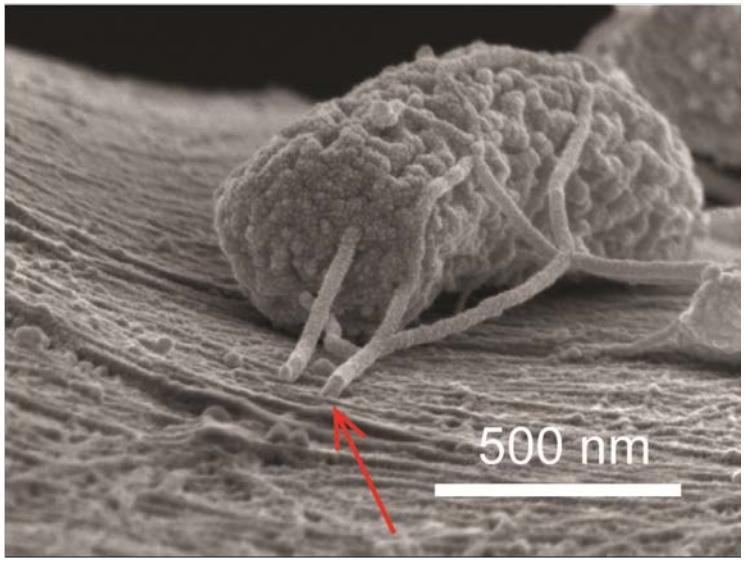


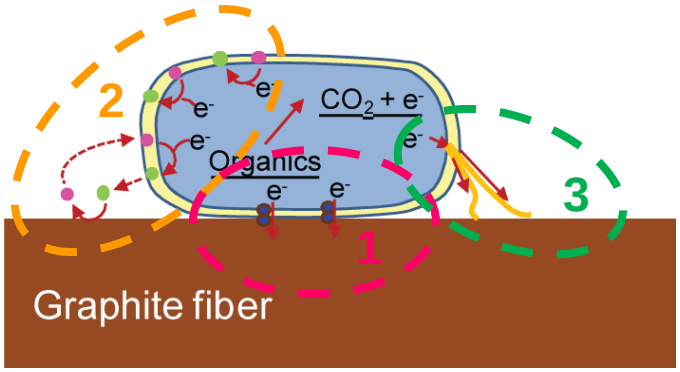


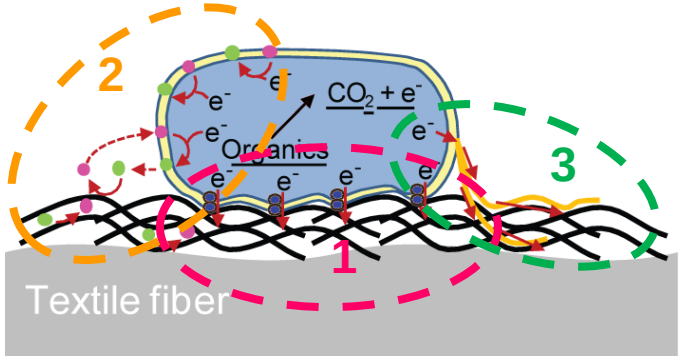
Biofilm-electrode interfacial area increased

Affinitive Electrode Surface

- Rough and soft
  - 1 **Direct membrane contact**
- Microscale porous
  - 2 **Electron mediators**
  - 3 **Microbial nanowires**







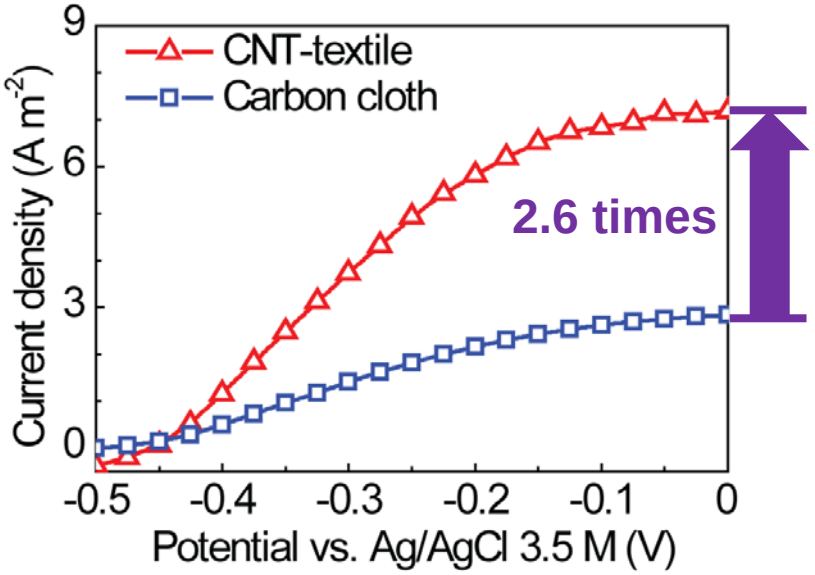
Carbon cloth vs. **CNT-textile**

Maximum Current Output

- Linear staircase voltammetry (LSV)

Carbon cloth (2.8 A/m^2)

vs. **CNT-textile (7.2 A/m^2)**

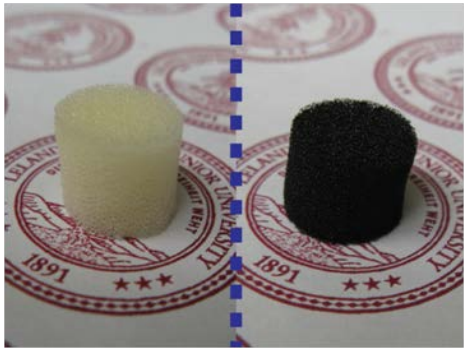


Internal colonization

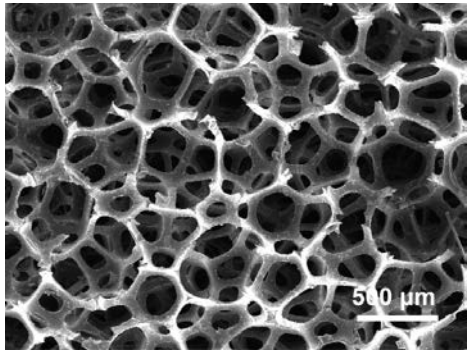
Affinitive electrode surface

CNT-Sponge

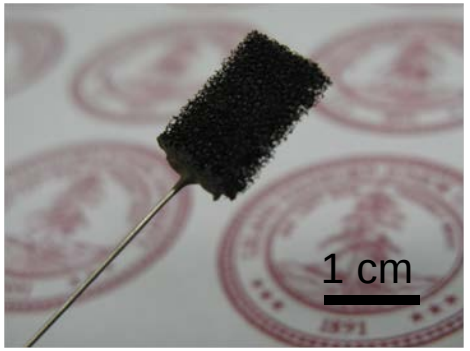
Fabrication



3D Framework

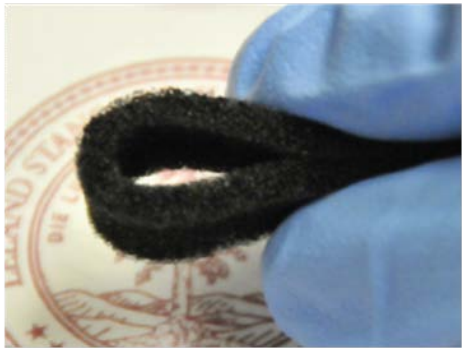


Isotropic

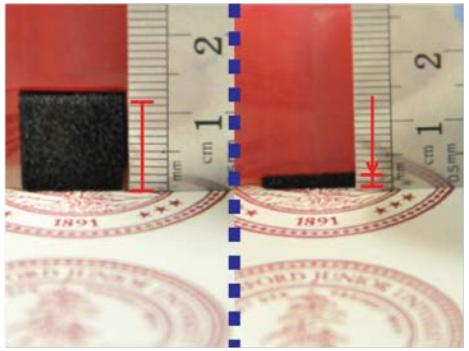


- Mechanical properties

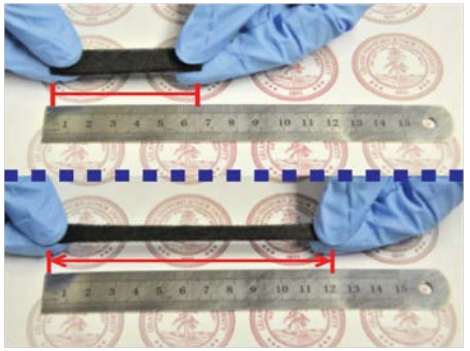
Flexible



Compressible

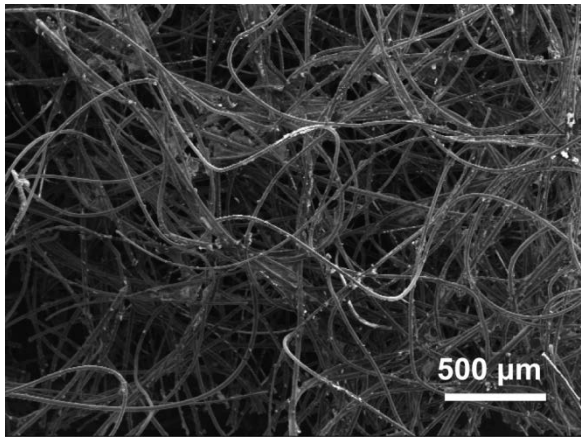


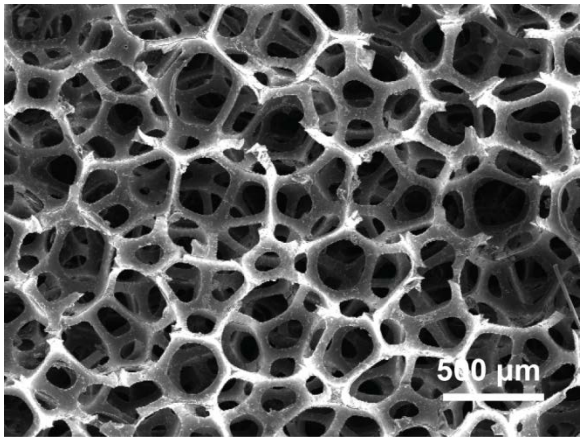
Stretchable

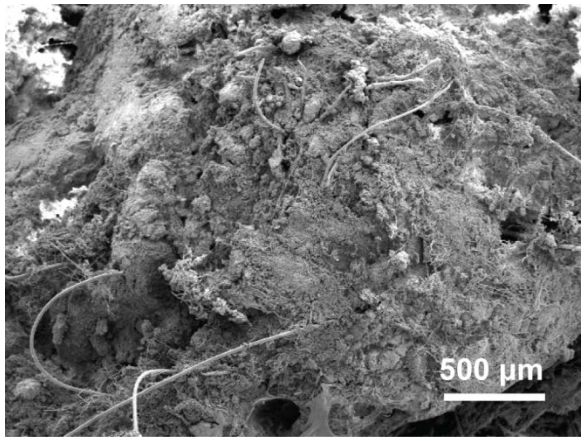


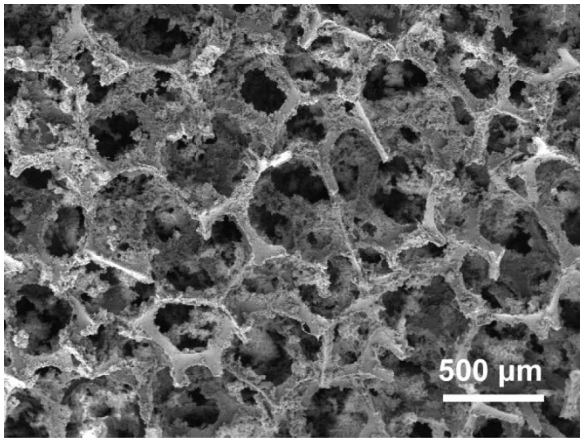
Macroscale Pores of CNT-Sponge

CNT-textile vs. **CNT-sponge**







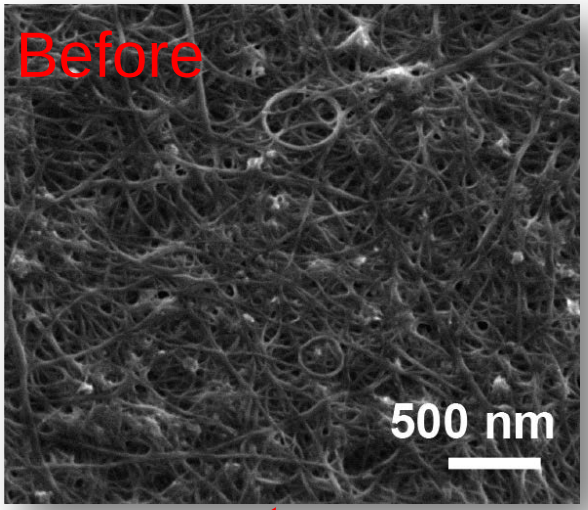


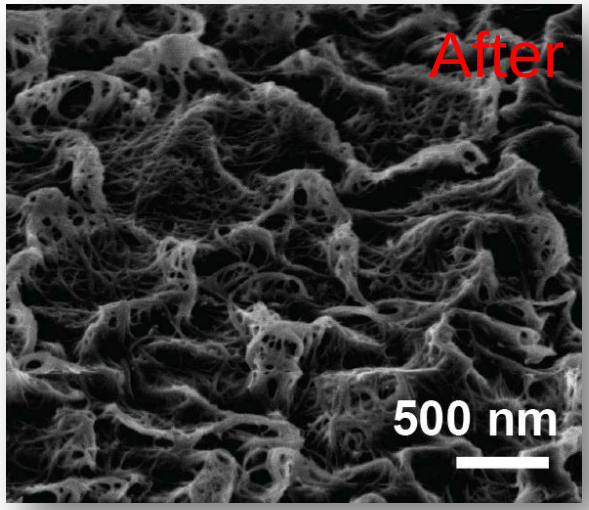
Uniform

Tunable

After 1-year operation in MFCs

Mesoscale Crinkling CNT Coating



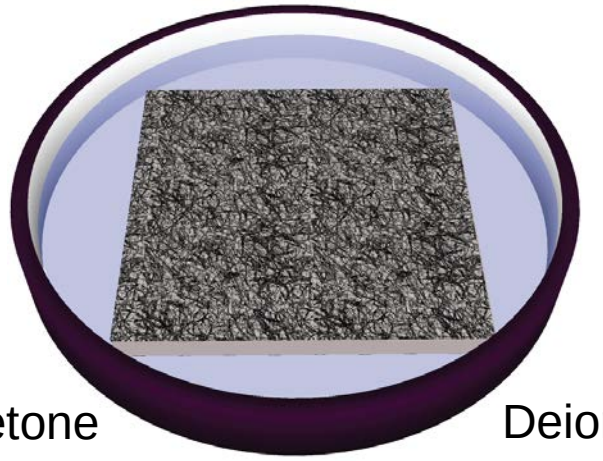


CNT-coated substrate

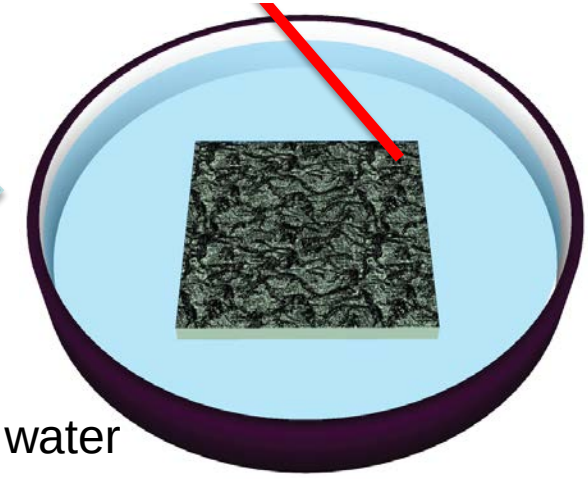
Expansion in solution 1

Shrinking in solution 2

Polyurethane sheet



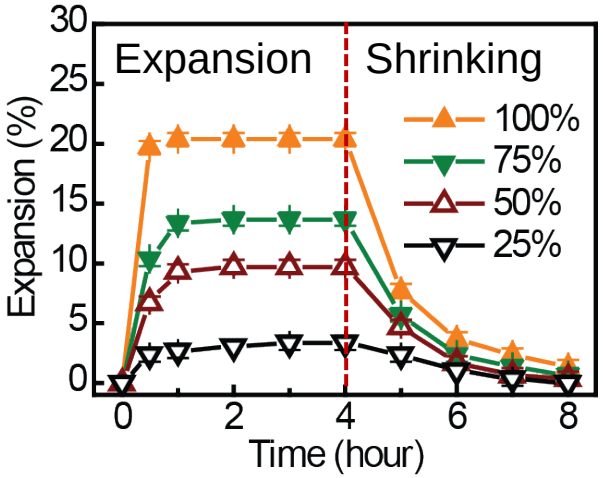
Acetone

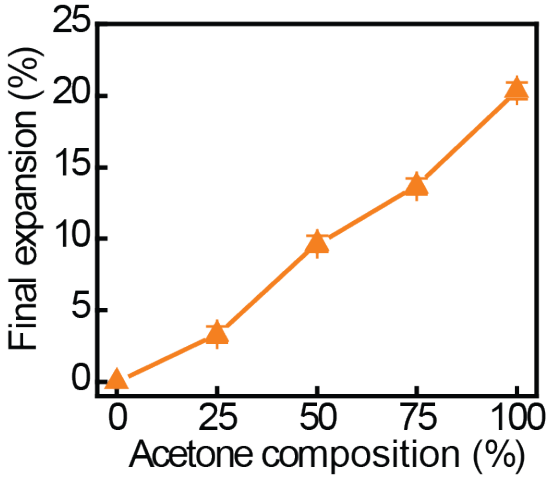


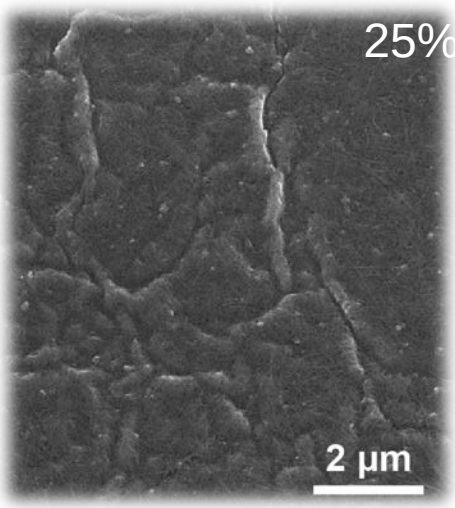
Deionized water

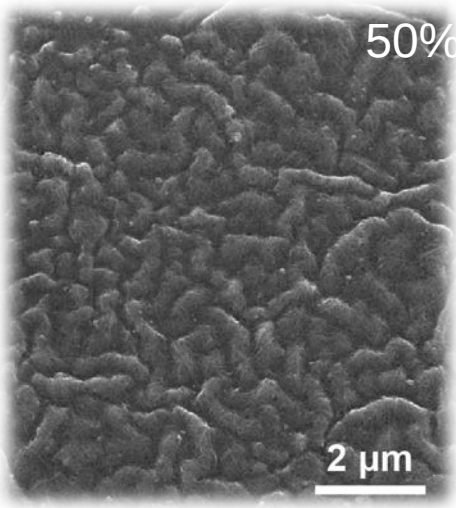
Crinkling Morphology: Controllability

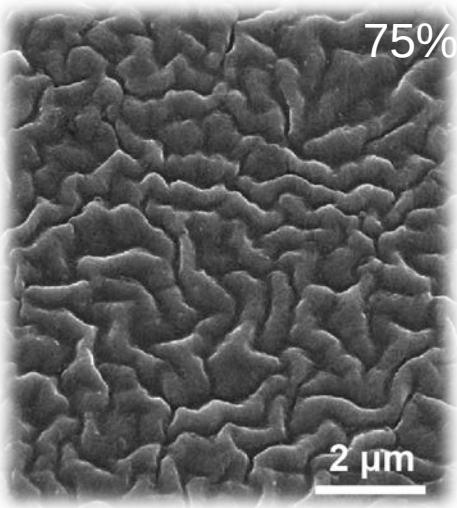
Varying acetone concentration

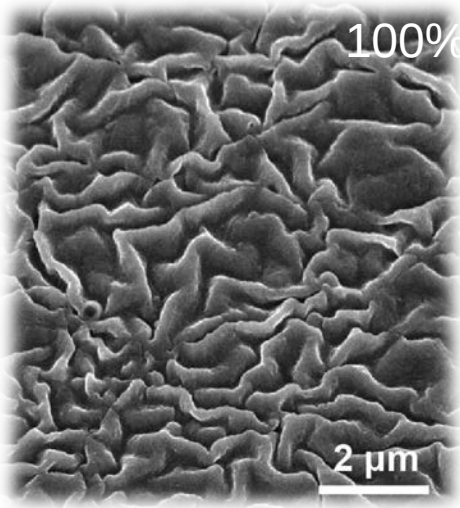




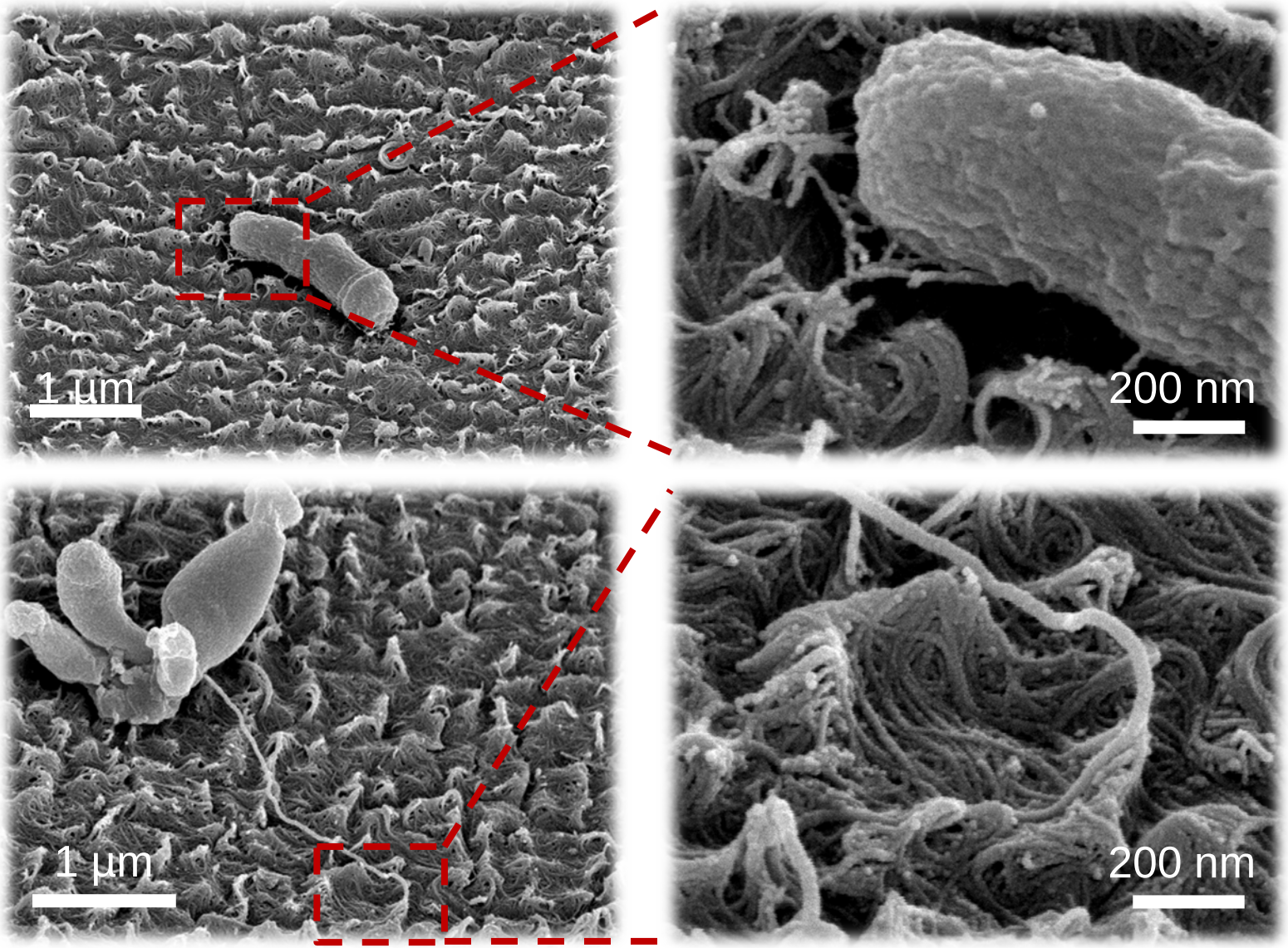








Microorganisms on Crinkling CNT Coating



Bioelectrodes: Criteria & Design

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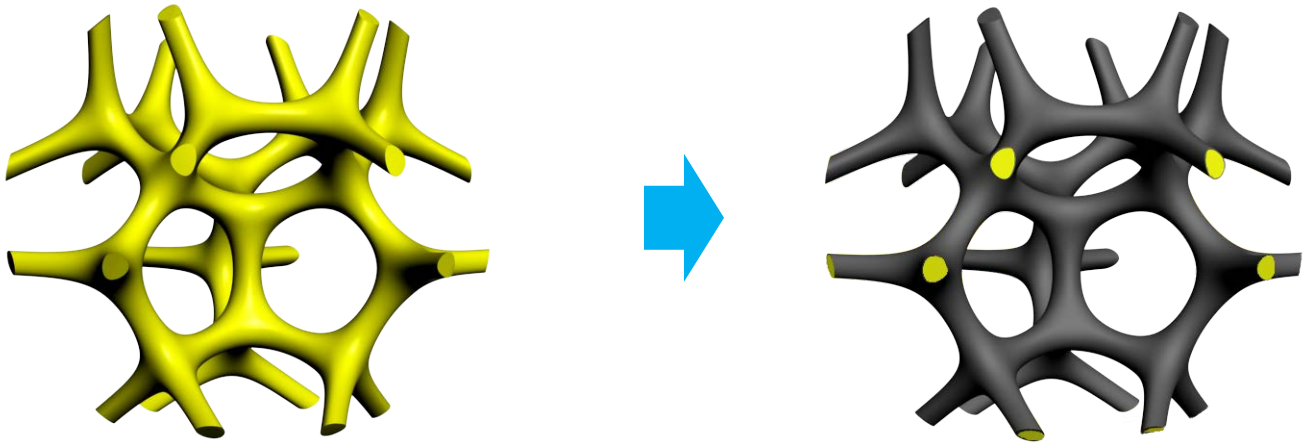
- **Macroscale porous structure**
- **Affinitive electrode surface**

More microbes for electron transfer

More efficient electron transfer



Take Home Messages

- Market of electrochemical devices is growing.
- New applications are emerging.
- Electrode design is critical.
- Nanotechnology is a powerful tool.

Thank You & Question