Nanotechnology and Water:

Environmental Applications & Implications

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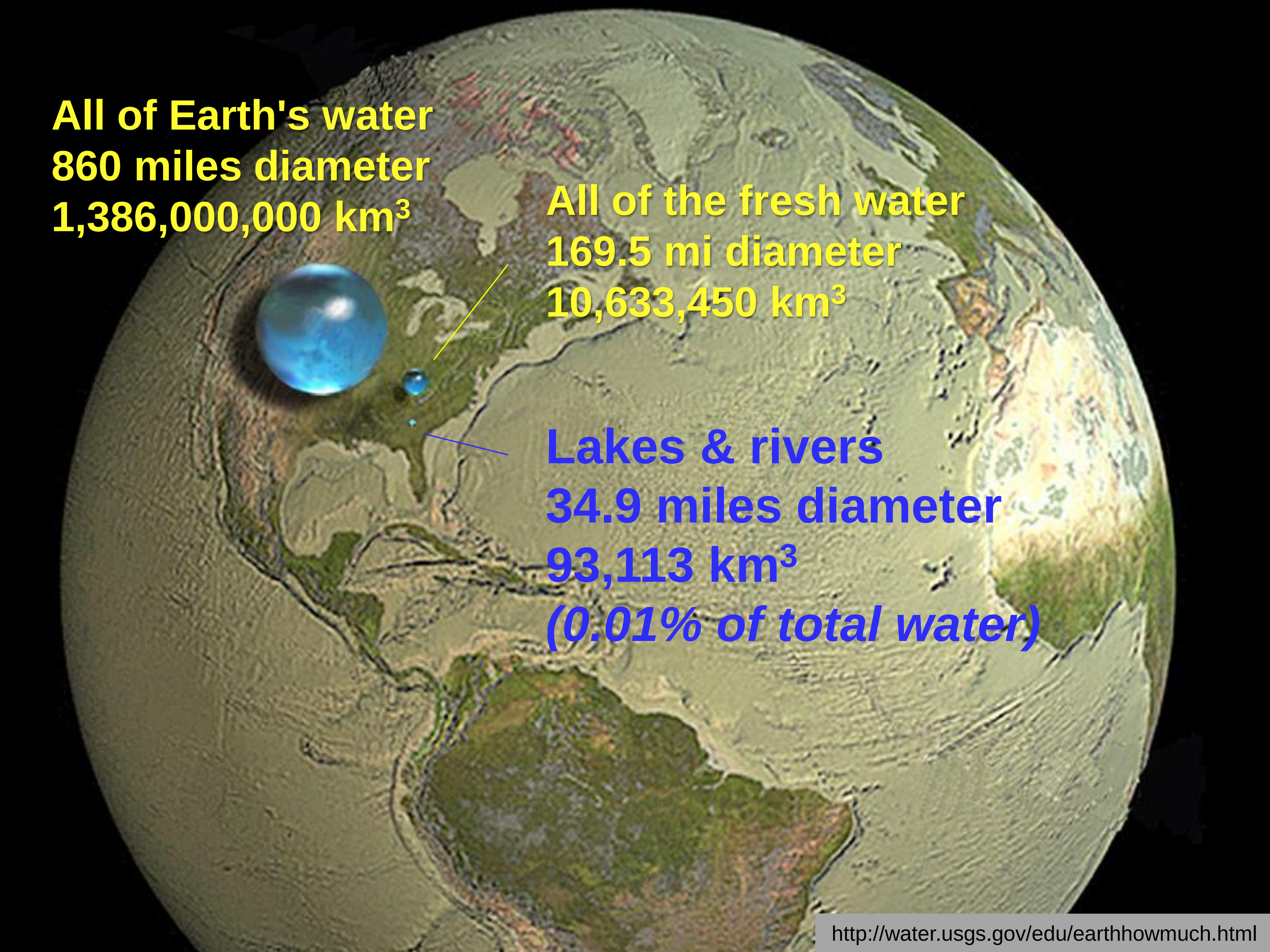
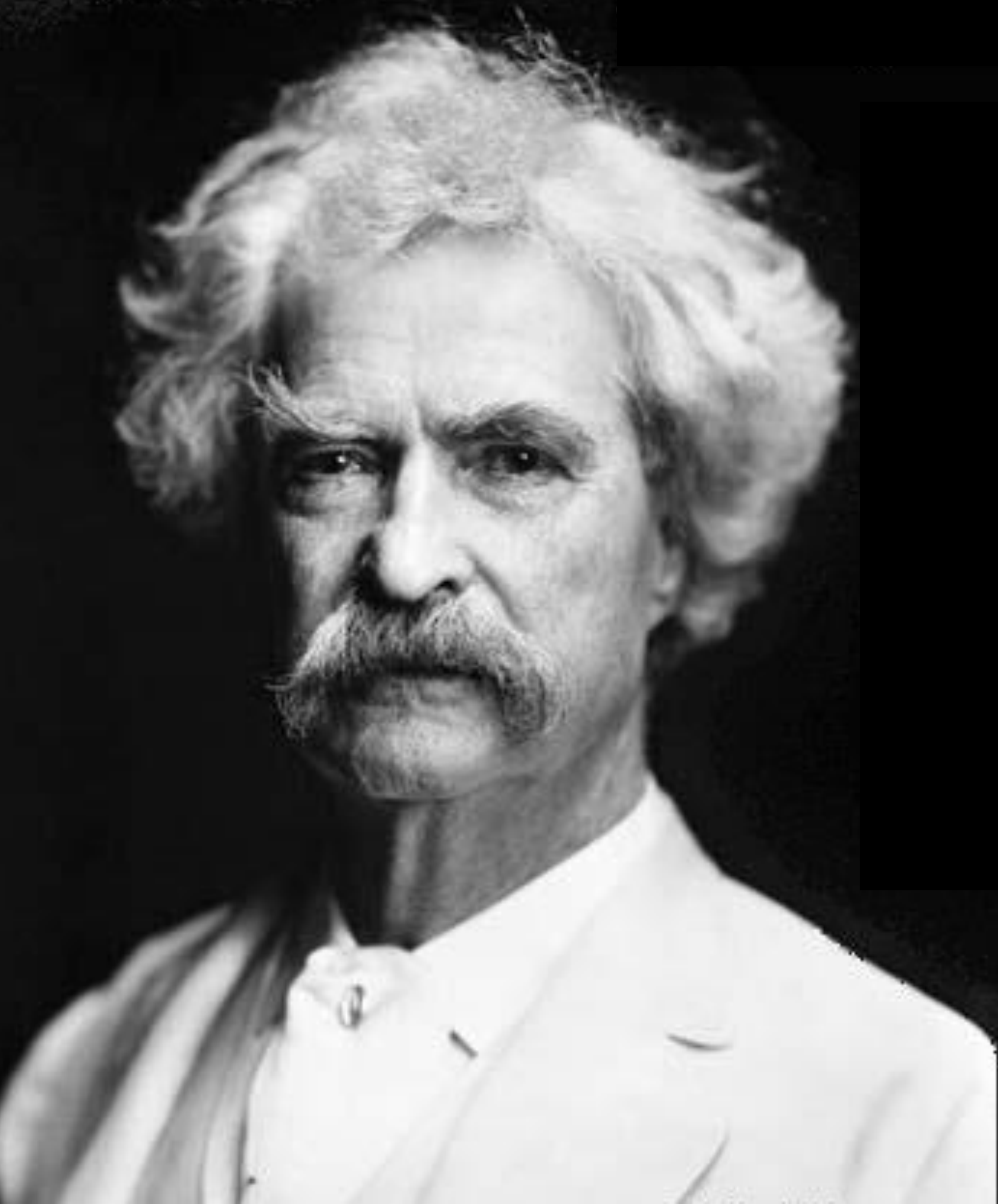
Sustainable Nanotechnology Organization

Marina del Rey, 5 November 2017

RICE ASU UTEP Yale


All of Earth's water
860 miles diameter
1,386,000,000 km³
All of the fresh water
169.5 mi diameter
10,633,450 km³
Lakes & rivers
34.9 miles diameter
93,113 km³
(0.01% of total water)
http://water.usgs.gov/edu/earthhowmuch.html



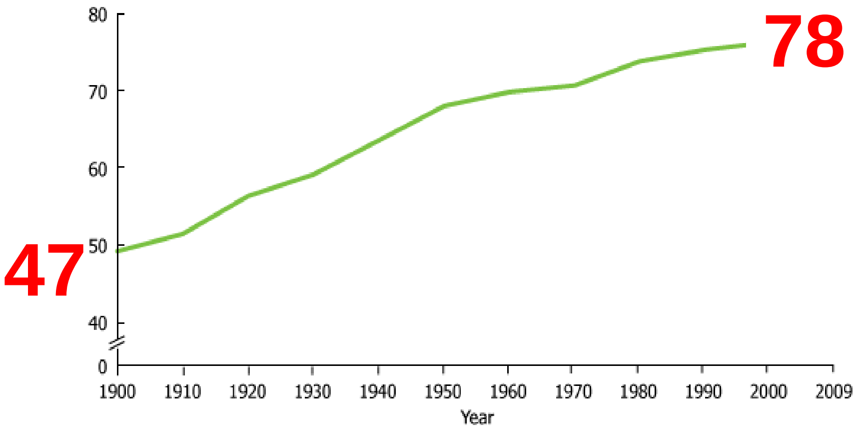
"Whiskey is for Drinking;

Water is for Fighting Over"

~Mark Twain

Clean Water Is Critical for Enhancing Human Capacity

American's life expectancy at birth



http://www.prb.org/Publications/Articles/2011/biodemography.aspx

- Public health
- Energy production
- Food security
- Economic development

- 43 million Americans lack access to municipal water; 800 million worldwide lack access to safe water
- Global market for drinking water ~ $700 billion
- Larger market for industrial wastewater reuse

VISION

Enable access to treated water almost anywhere in the world, by developing transformative and off-grid modular treatment systems empowered by nanotechnology that protect human lives and support sustainable development.

Focus on Two Applications

- Off-grid humanitarian, emergency-response and rural **drinking water** treatment systems

https://www.globalgiving.co.uk/projects/clean-water-for-peru/updates/

- Industrial **wastewater reuse** in remote sites (e.g., oil and gas fields, offshore platforms)

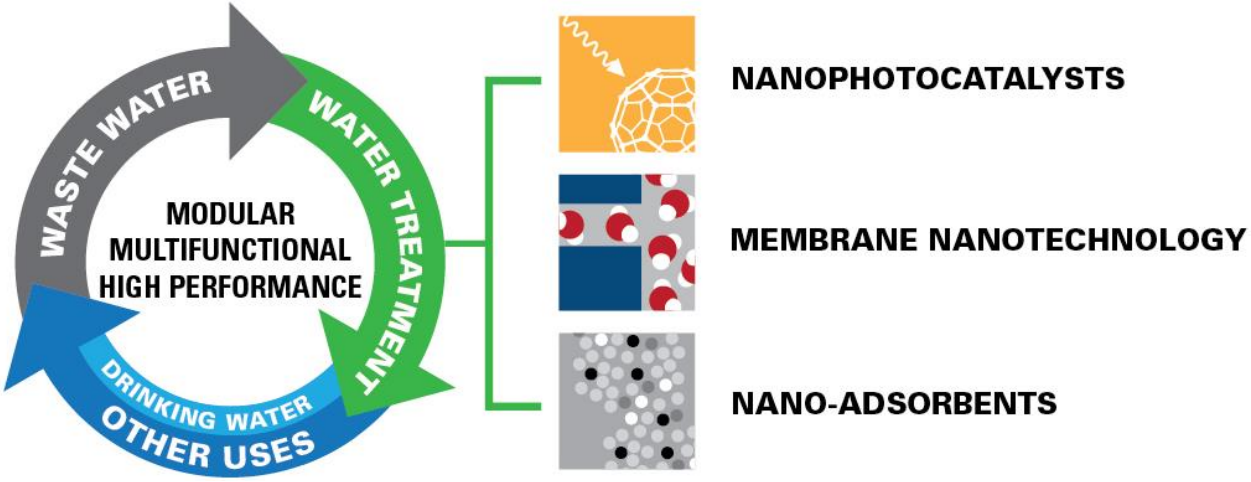
http://switchboard.nrdc.org/blogs/rhammer/fracking-2.jpg

Why Nano?

Leap-frogging opportunities to:

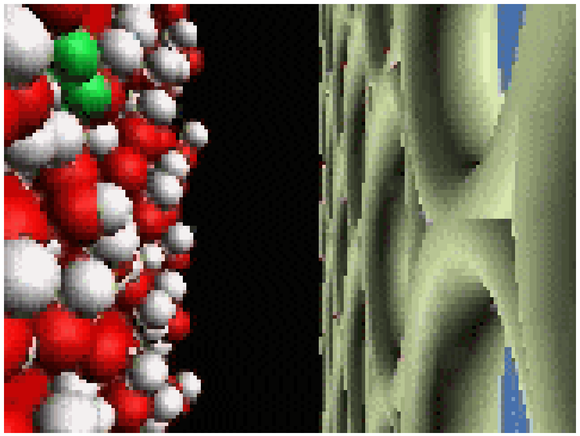
- Tap unconventional water sources, & reduce cost of remote water treatment *(multifunctionality and higher selectivity)*

- Transformative, modular and more efficient chemical treatment processes that harvest solar energy to lower costs and generate less waste

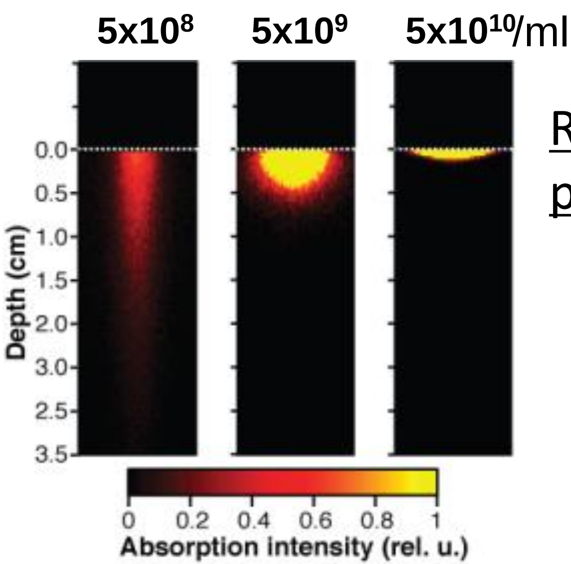


Nanophotonics-Enhanced Membrane Distillation

Membrane Distillation



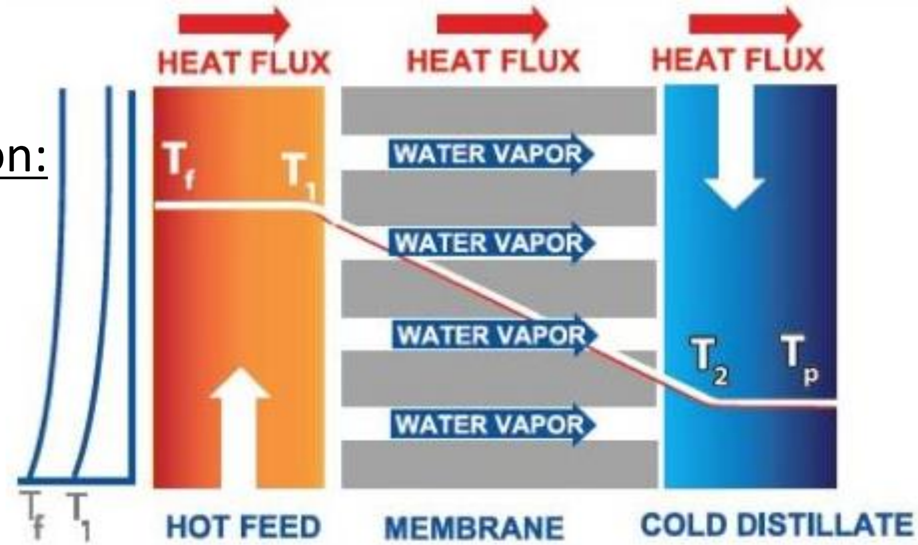
www.desalination.biz



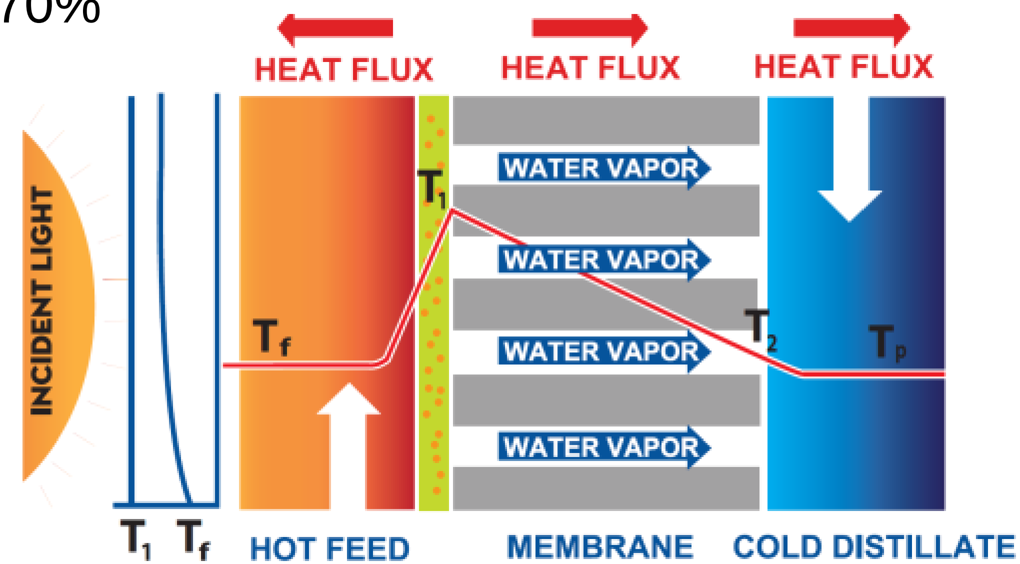
Temp. polarization:

$$a = \frac{T_1 - T_2}{T_f - T_p}$$

Reduces T gradient by up to 70%

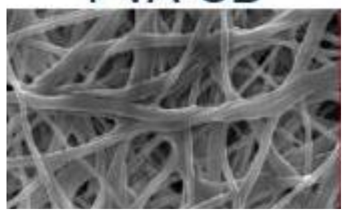


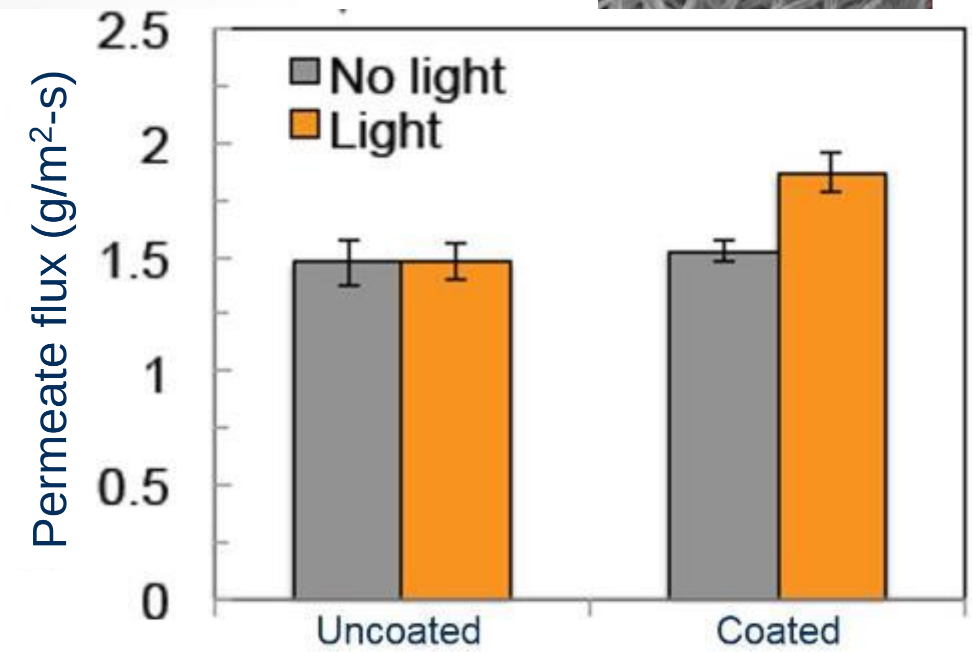
Reverse temp. polarization:



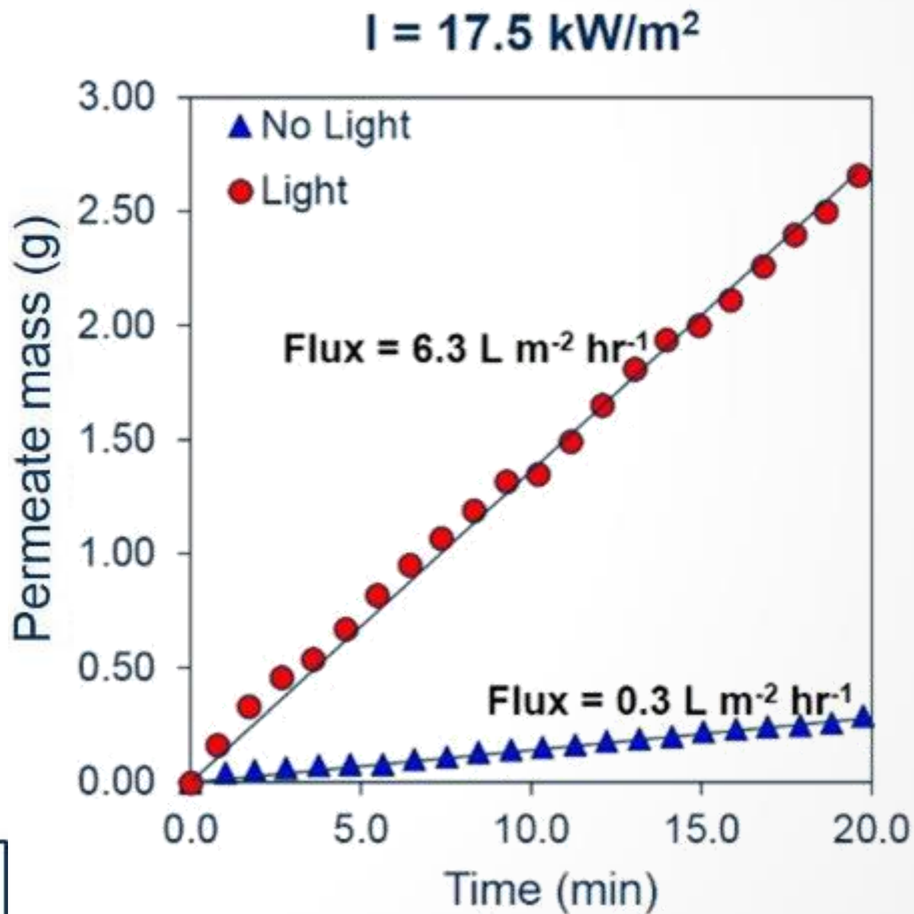
Photothermal Coating Enhances Membrane Permeate Flux

PVA-CB





Tf = 35 ° C, Tp = 20 ° C
Light source: simulated sunlight at 1 sun unit

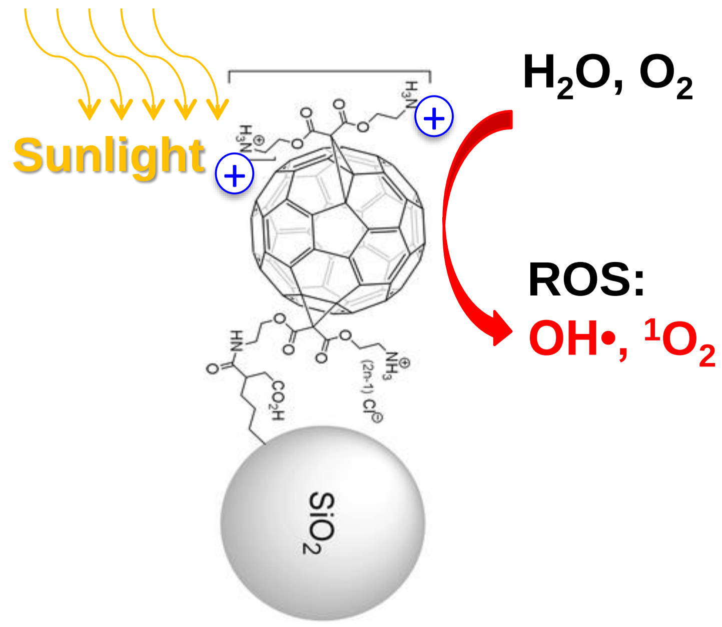


Pilot Solar MD

Desalinates 8 L of seawater in 8 hours (enough DW for 4)

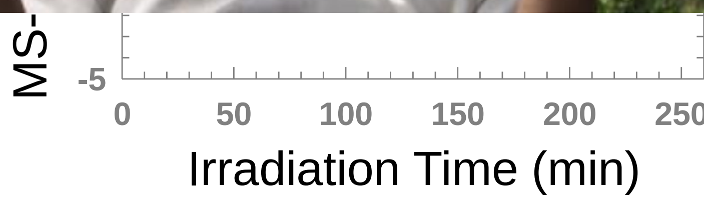
(Photo)Disinfection & Advanced Oxidation

- Nano(photo)catalysts that use solar radiation to generate ROS that destroy resistant microbes and recalcitrant pollutants without harmful disinfection byproducts
- Bait and hook approach to attract pollutant to site of ROS generation

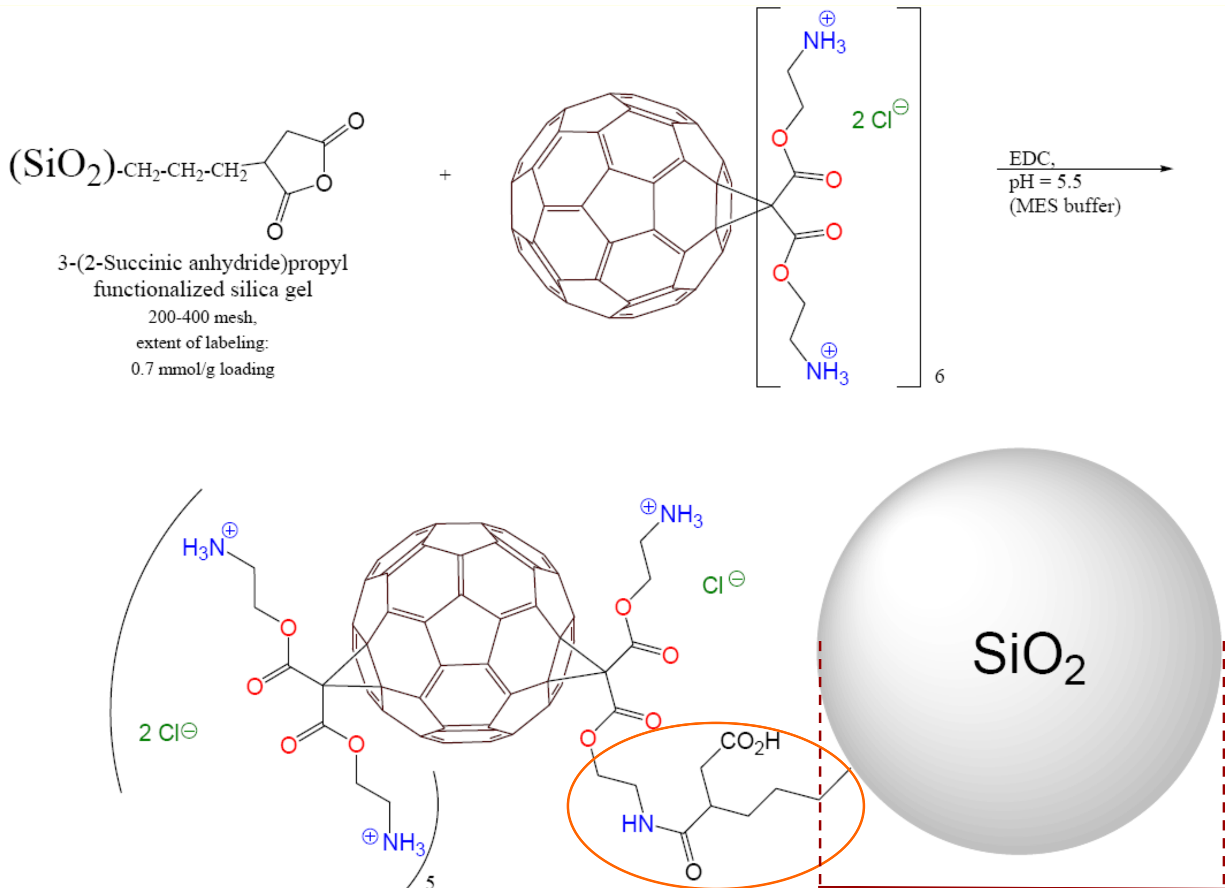


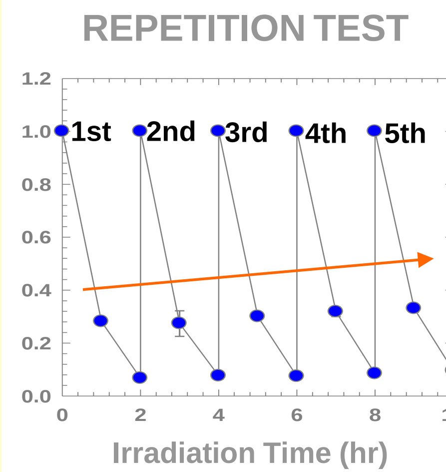
Immobilized Photocatalyst

Advantages of Amino-C_{60} as Photocatalytic Disinfectant



Immobilization of aminofullerene onto silica beads facilitates separation, reuse and recycling





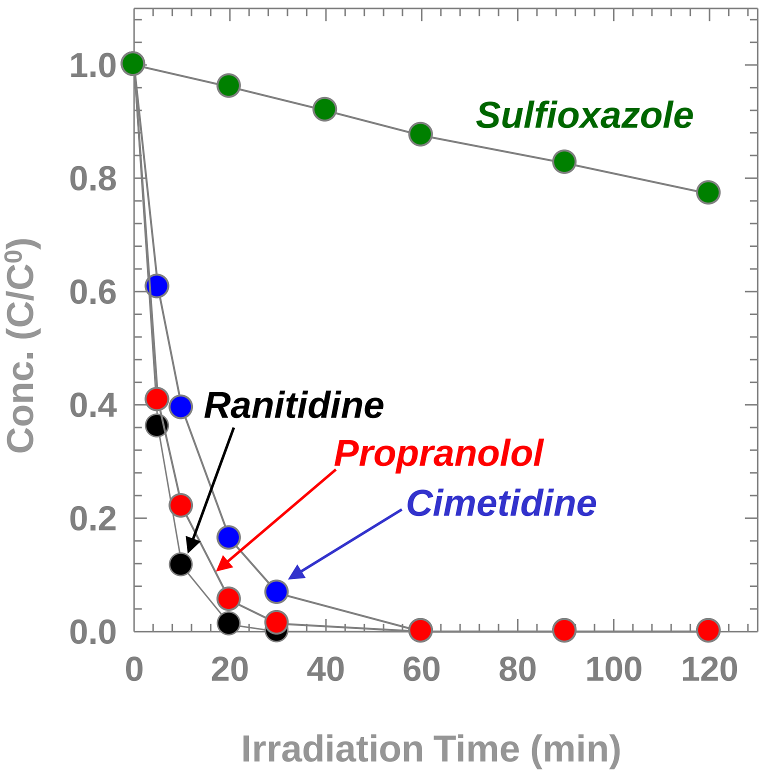
No loss of photo-activity

0.2 - 0.3 mm
EASILY SEPARABLE

NO C_{60} AGGREGATION ON THE SILICA SURFACE (HIGHER CATALYTIC AREA)

Lee, Mackeyev, Cho, Wilson, Kim and Alvarez (2010). *Environ. Sci. Technol.* 44: 9488–9495.

Photocatalytic treatment could also polish WWTP effluents (pharmaceuticals, endocrine disruptors)

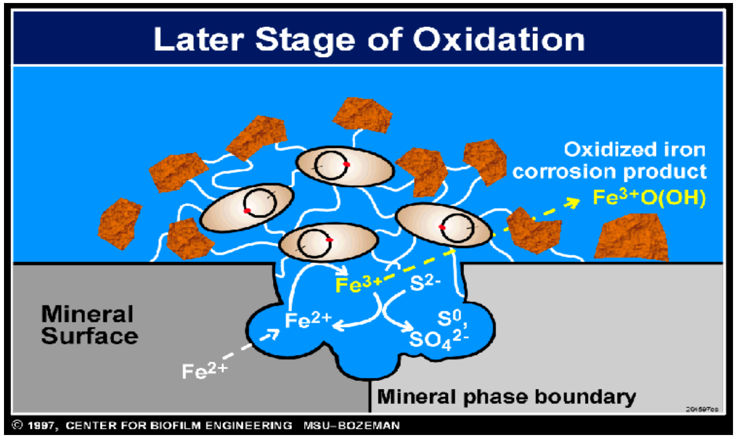


Lee J., S. Hong, Y. Mackeyev, C. Lee, L.J. Wilson, J-H Kim and P.J.J. Alvarez (2011). Environ. Sci. Technol. *45*: 10598–10604.

Biofilms

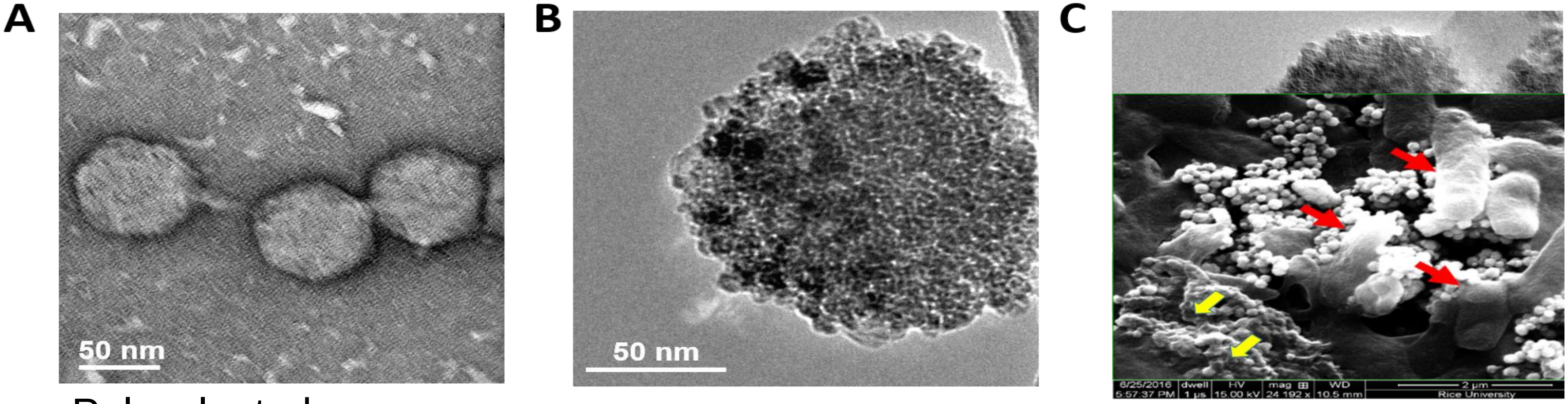
- Surface attached community of microorganisms embedded in a “slimy” matrix
  - Polysaccahrides
  - Protein
  - Lipids
- **Can harbor problematic bacteria (pathogens, corroders)**
- **Difficult to eradicate** (limited penetration by chemical disinfectants)

- Can cause corrosion through
  - Production of organic acids
  - Depassivation of surfaces
  - Cathodic depolarization
  - Direct attack of a component



Source: http://www.biofilm.montana.edu/resources/images/biofilms-nature/oxidation-late-stage.html

Phage conjugation with magnetic colloidal nanoparticle clusters (CNCs) for enhanced biofilm penetration under a weak magnetic field

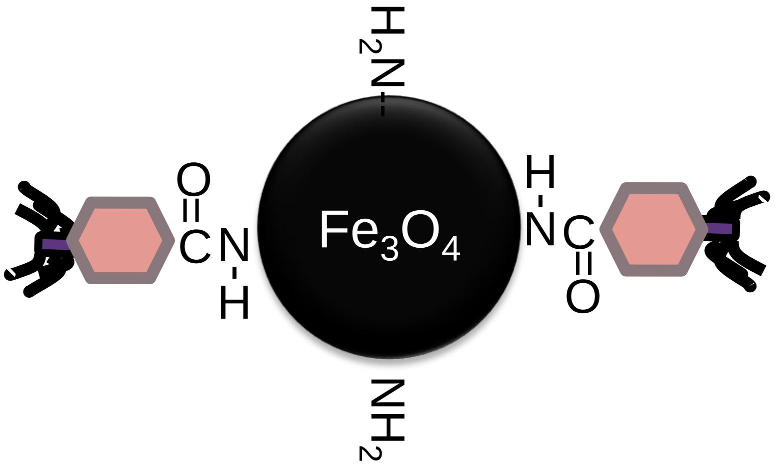


Polyvalent phages

Chitosan-coated Fe_3O_4

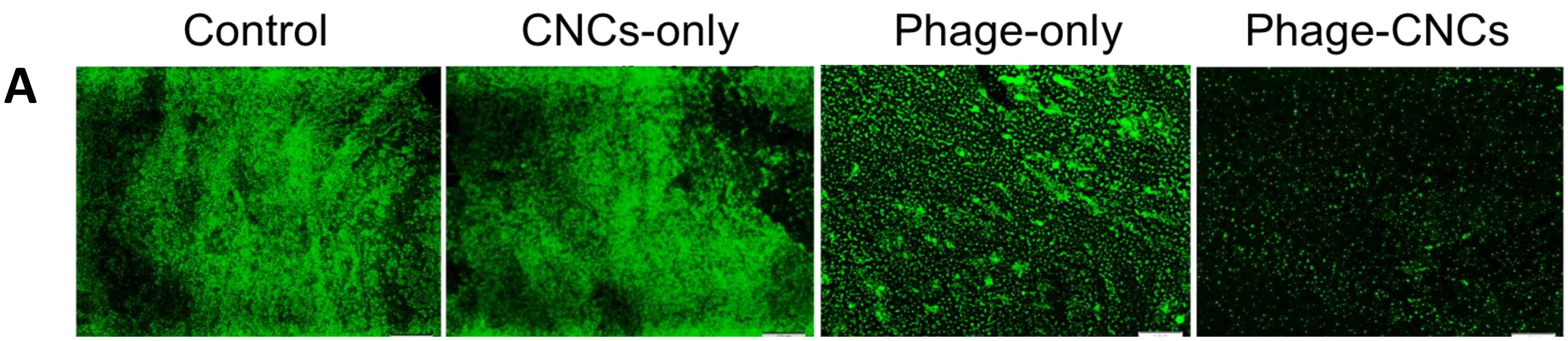
CNCs infecting bacteria

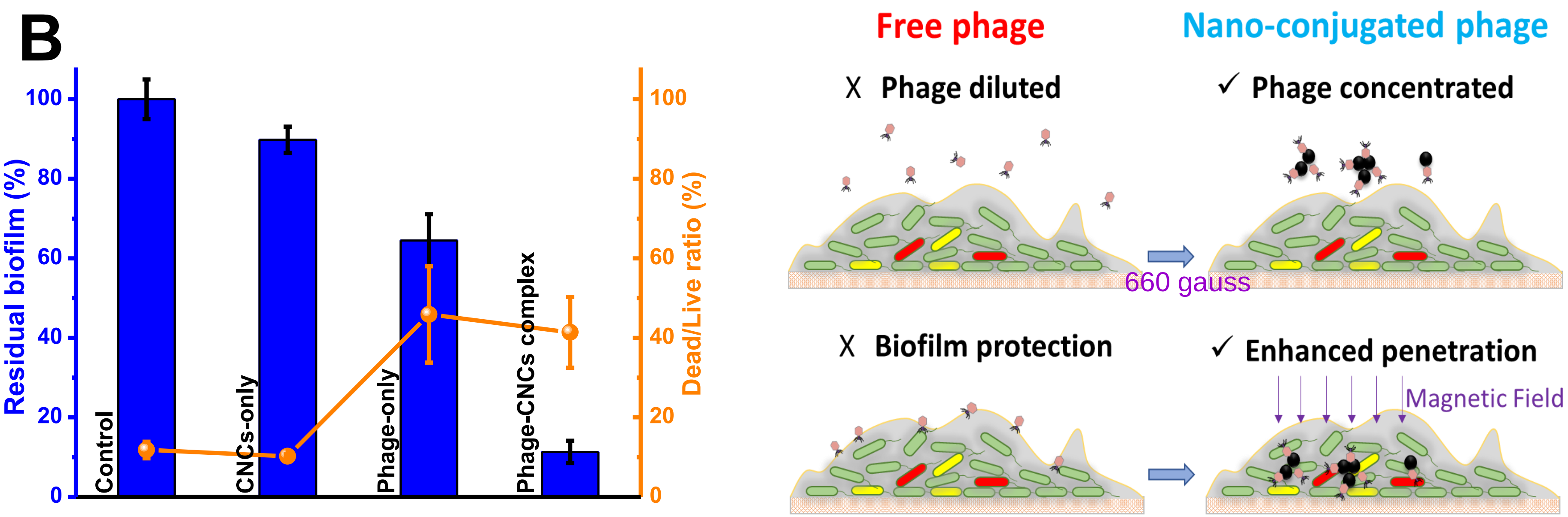
Phage tail recognizes target bacteria →



Li *et al* (2017) Environ. Sci. Nano. 4: 1817–1826

Phage-CNCs complexes are more effective at penetrating & treating biofilms than free phages





Summary of Accomplishments

- Low-energy (solar-driven) desalination by nanophotonic MD or electrosorption
- Disinfection without harmful byproducts and selective advanced (photo)oxidation
- Selective nano-sorbents
- Fouling-resistant membranes

"People don't know what they want until you show it to them"

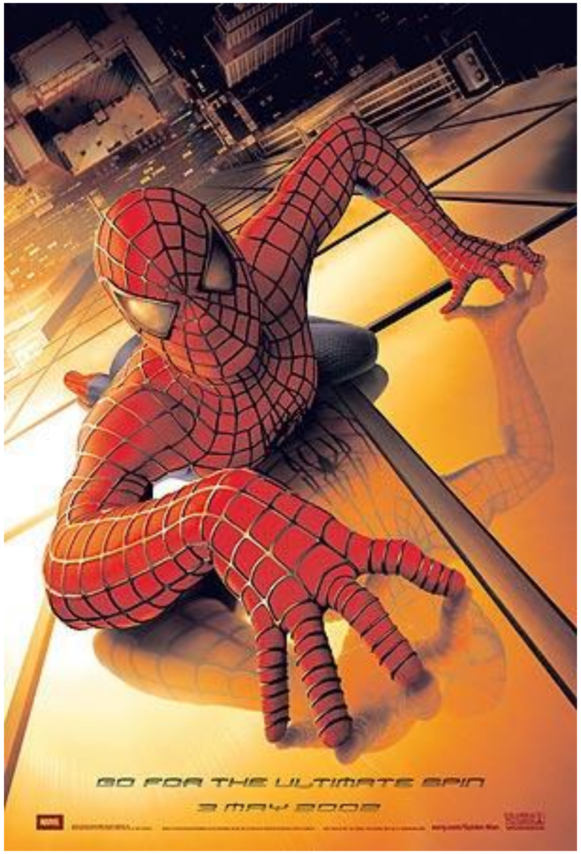
– Steve Jobs

Responsible Nanotechnology

"With Great Power, Comes Great Responsibility"

Uncle Ben to Peter Parker in Spider Man

Paul Hermann Muller
Thomas Midgley



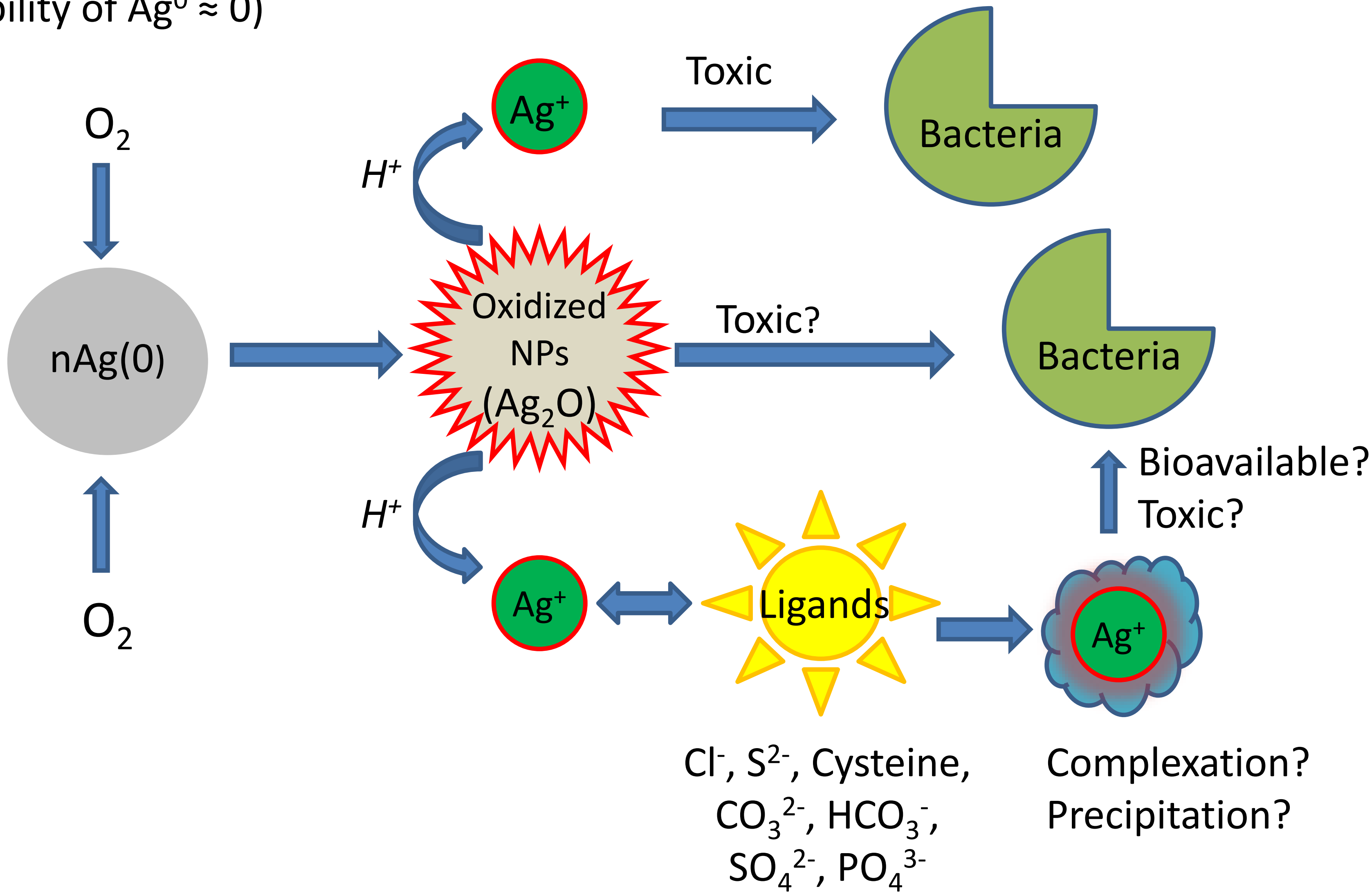
Silver Nanoparticles (AgNPs):
Toxicity Mechanisms & Unintended Consequences

Is the antimicrobial activity of silver due to the nanoparticles themselves, or to the released Ag^+ ions, or both?

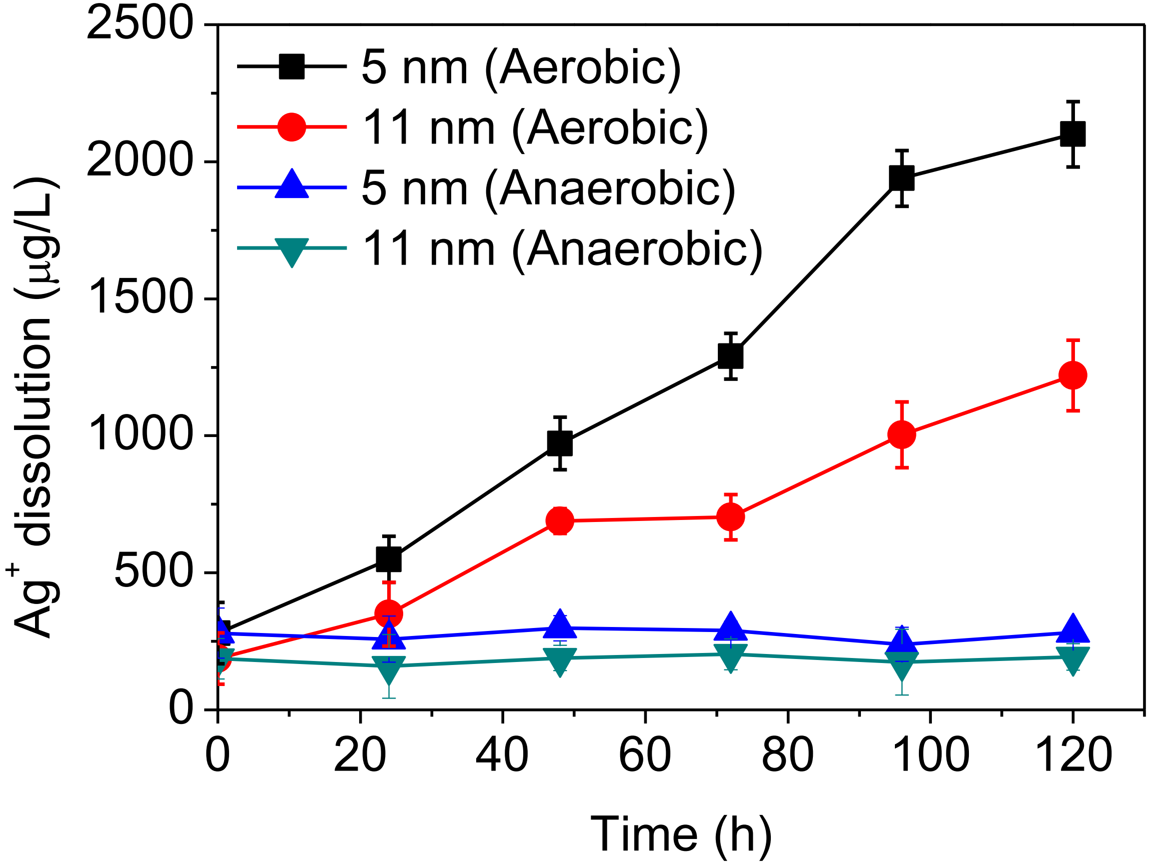
- And how do environmental conditions and water chemistry affect their relative influence?

Bioavailability and Toxicity of nAg

Ag^+ is released only if nAg(0) is oxidized: $4Ag^0 + O_2 + 4H^+ \leftrightarrow 4Ag^+ + 2H_2O$
(Solubility of $Ag^0 \approx 0$)

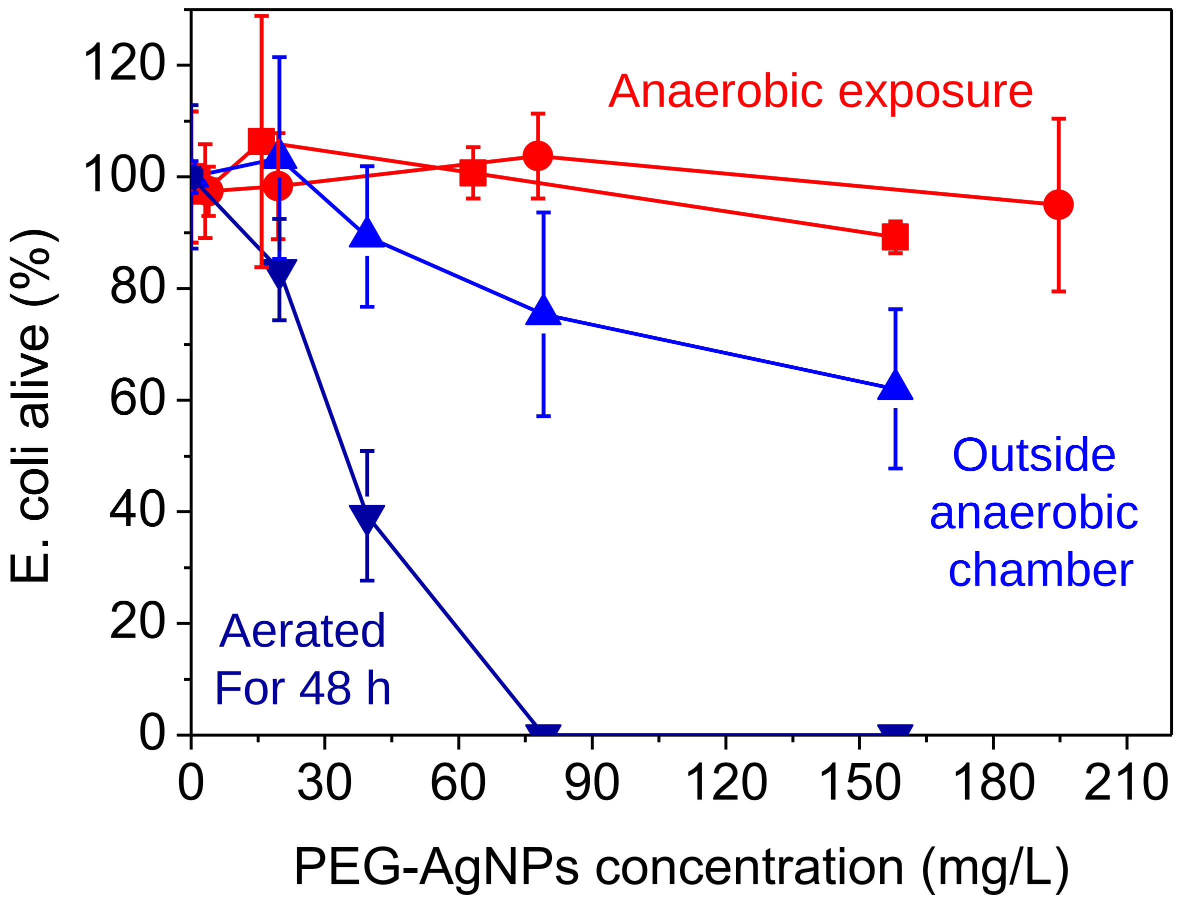


No Ag^+ release under Anaerobic Conditions
(Faster release for air-exposed smaller particles)



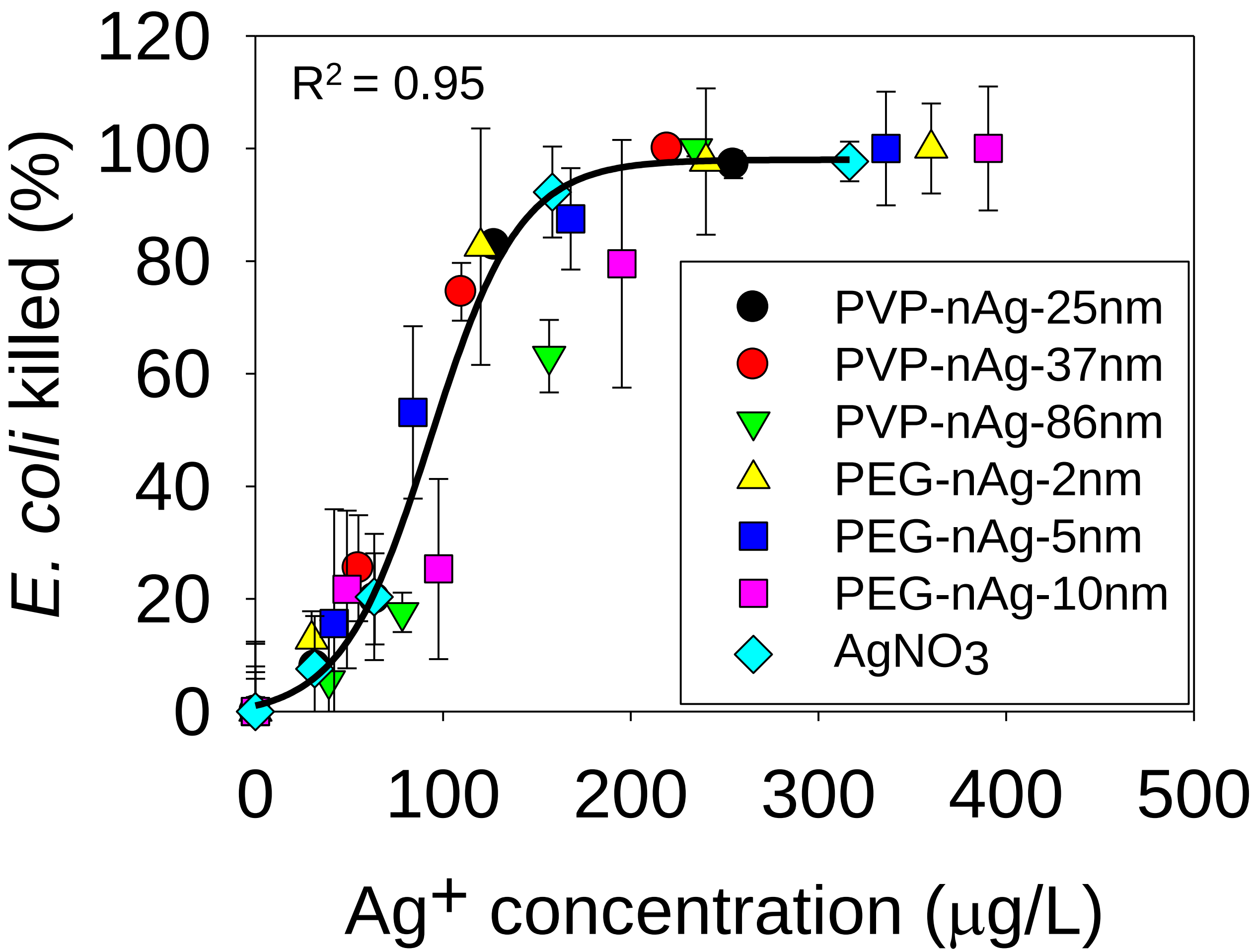
Xiu Z., Q. Zhang, H.L. Puppala, V.L. Colvin, and P.J.J. Alvarez (2012). Nanoletters. 12, 4271−4275.

No Toxicity Without Ag^+ Release



Xiu Z., Q. Zhang, H.L. Puppala, V.L. Colvin, and P.J.J. Alvarez (2012). Nanoletters. 12, 4271−4275.

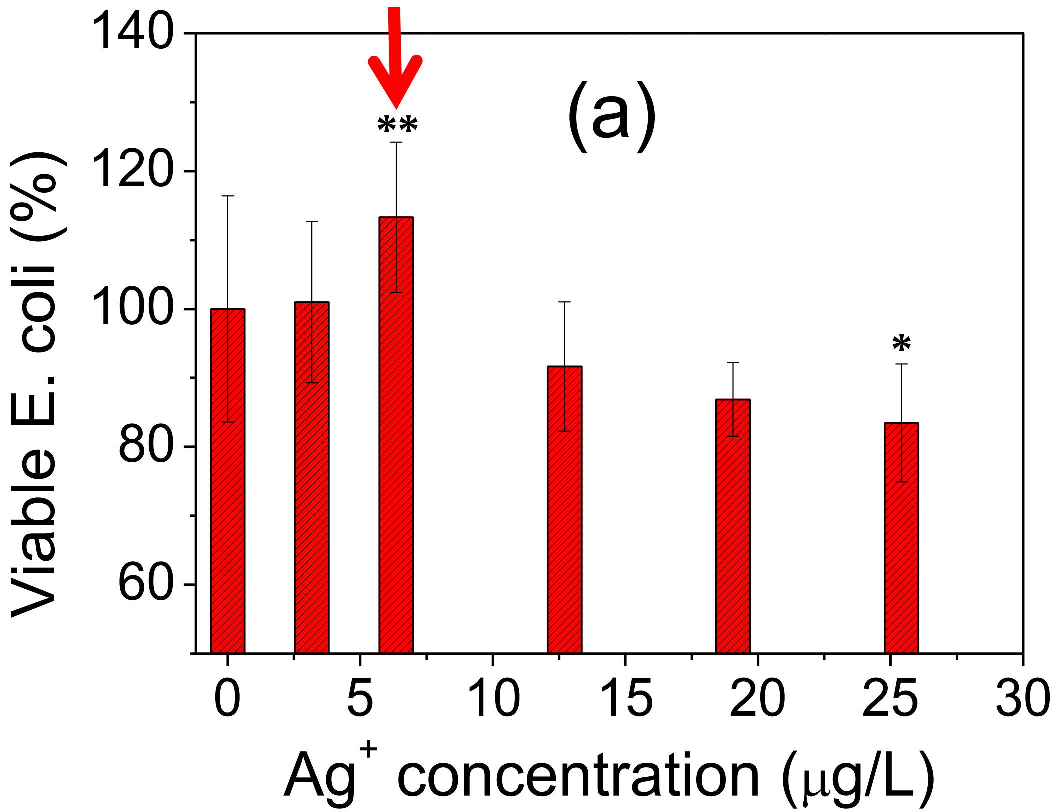
nAg Toxicity Can Be Explained by Dose-Response of Released [Ag^+]



Xiu Z., Q. Zhang, H.L. Puppala, V.L. Colvin, and P.J.J. Alvarez (2012). Nanoletters. 12, 4271−4275.

“What does not kill you makes you stronger”

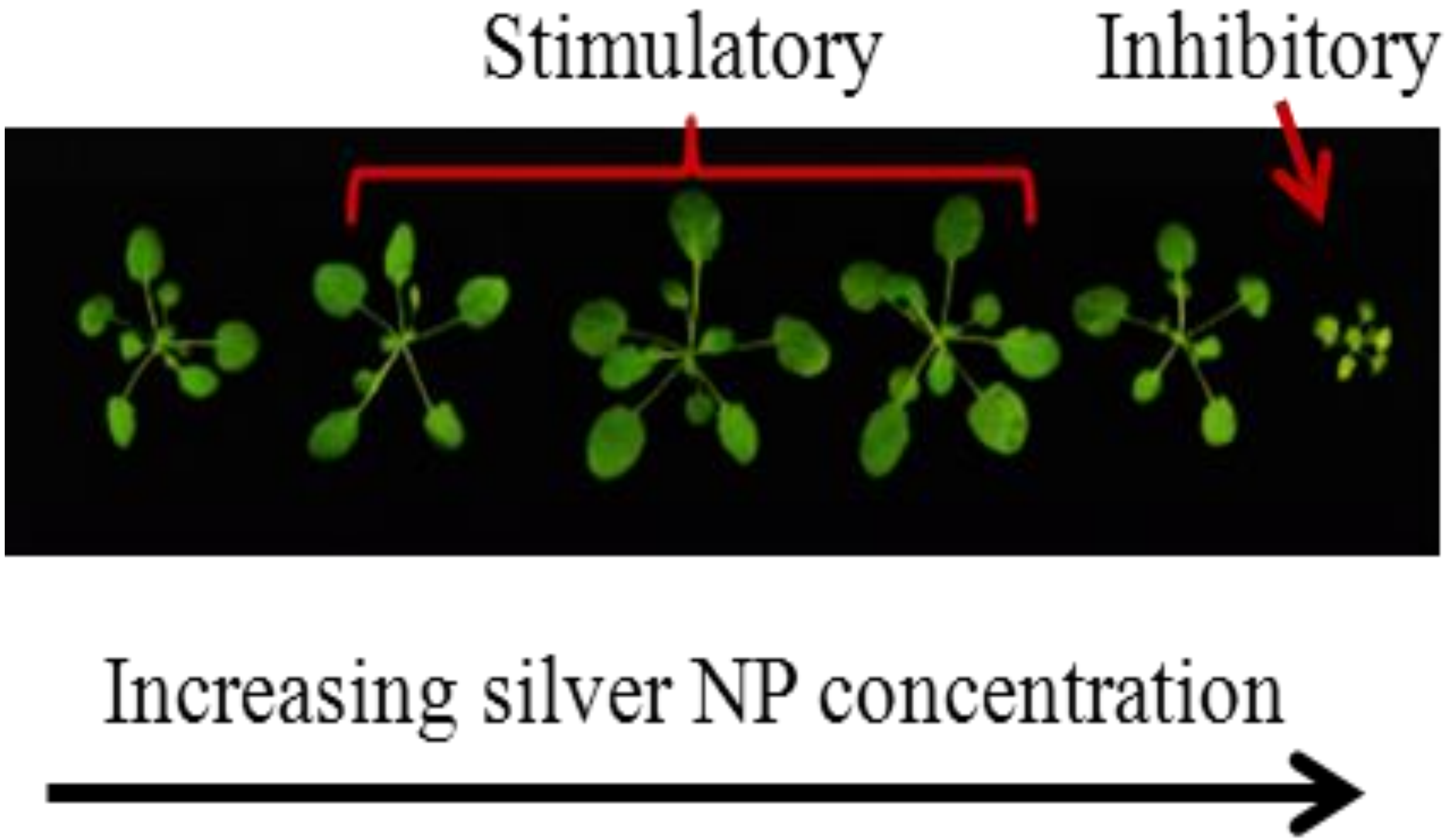
Friedrich Nietzsche



Stimulatory effect after 6 h exposure to sublethal Ag^{+} concentration

(Hormesis?)

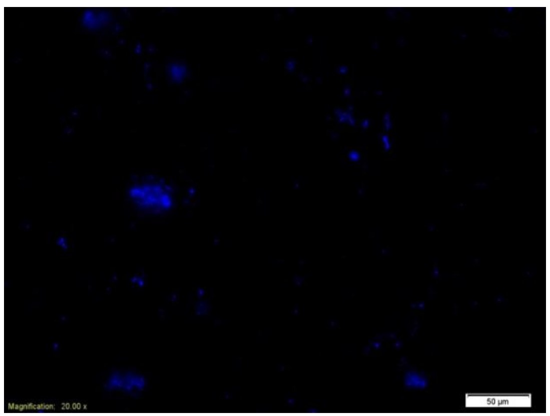
Xiu Z., Q. Zhang, H.L. Puppala, V.L. Colvin, and P.J.J. Alvarez (2012). Nanoletters. 12, 4271−4275.



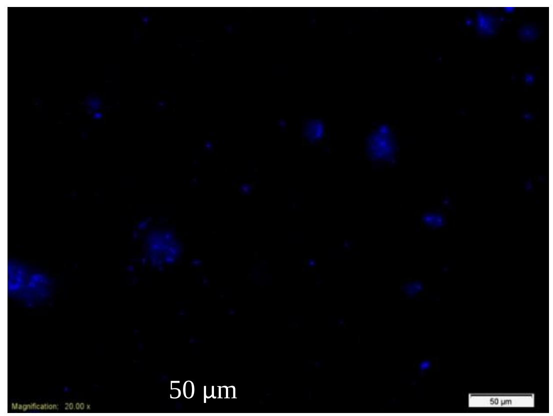
Wang J., Y. Koo, A. Alexander, Y. Yang, S. Westerhof, Q. Zhang, J. Schnoor, V. Colvin, J. Braam, and P.J. Alvarez (2013). Environ. Sci. Technol. 47 (10): 5442–5449.

Sublethal Exposure to AgNPs (but not to Ag^+) stimulated **biofilm** development

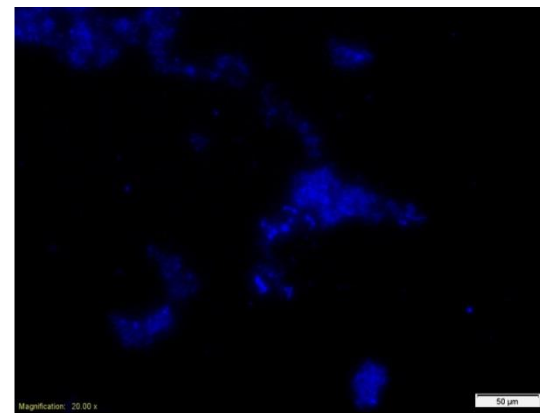
Mixed culture from the effluent of a WWTP, forming biofilm on a glass slide



Control



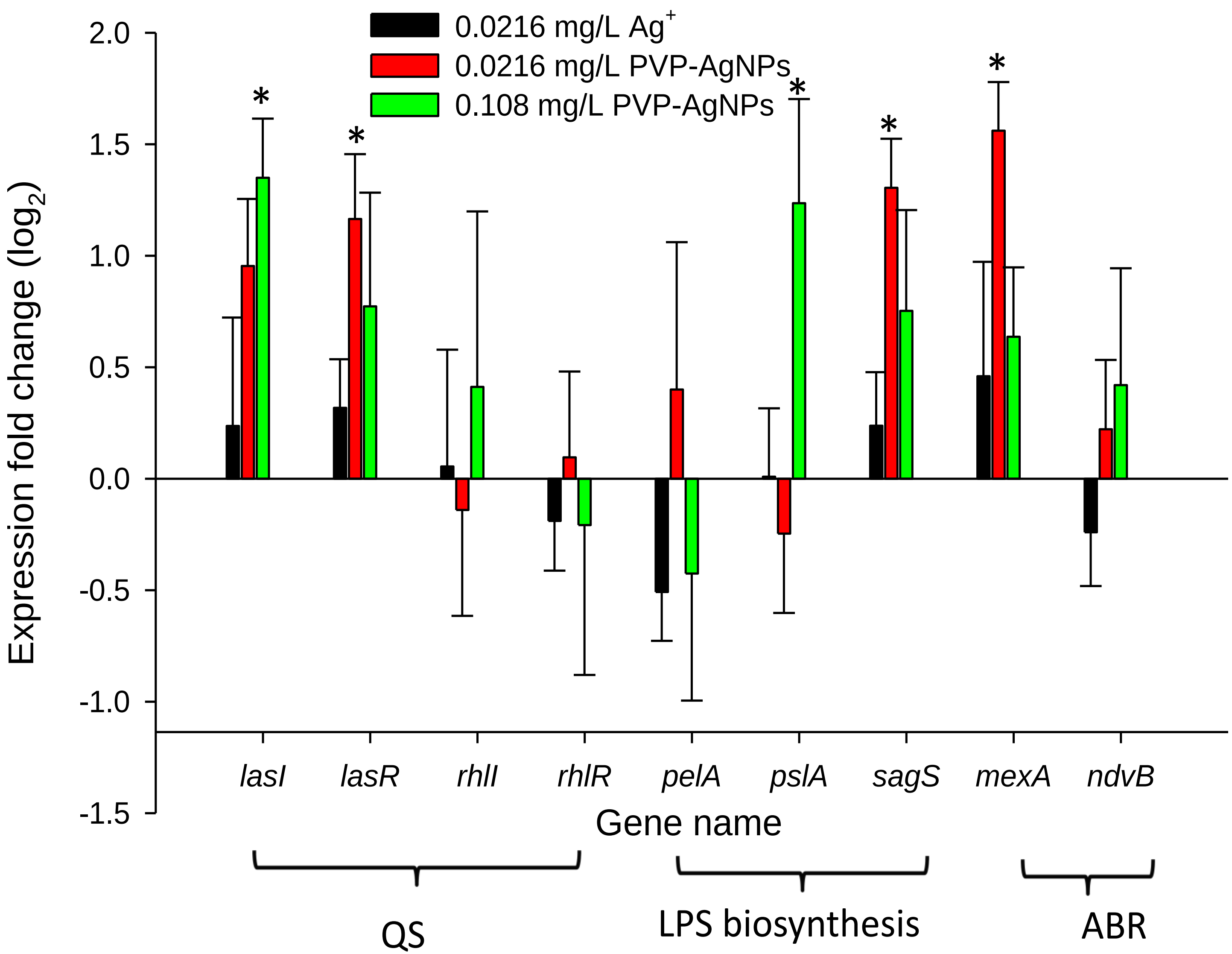
0.02 mg/L of Ag^+



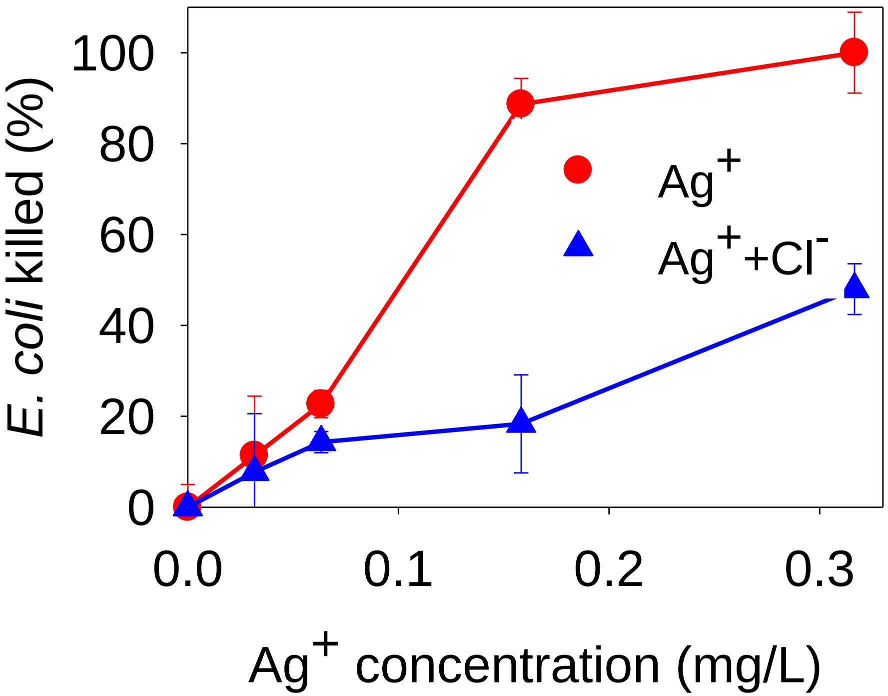
0.02 mg/L of AgNPs

Yang & Alvarez (2015). ES&T Letters. DOI: 10.1021/acs.estlett.5b00159

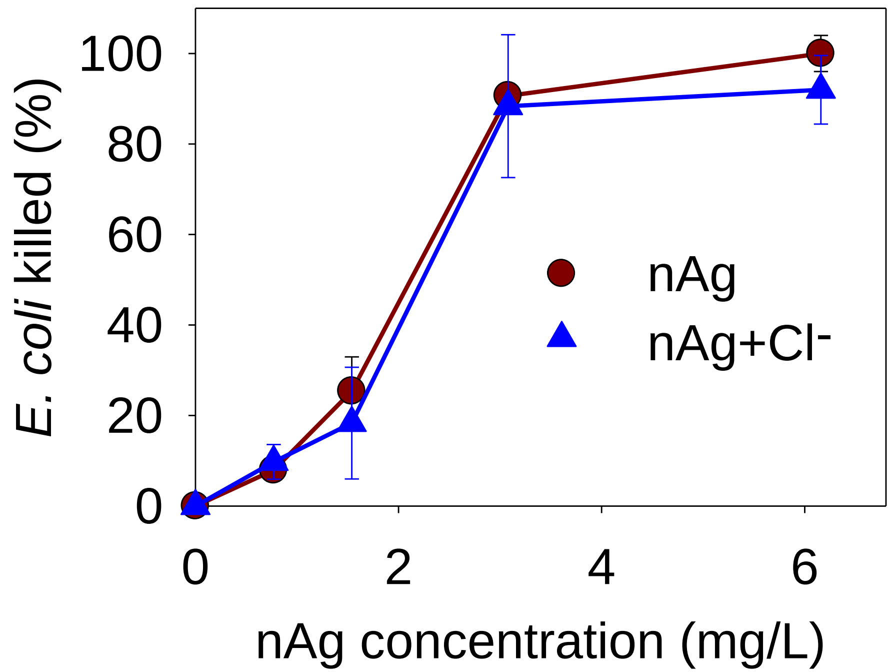
Sub-lethal exposure of *P. aeruginosa* to AgNPs Upregulates Quorum Sensing, LPS, & Antibiotic Resistance Genes



Why is nAg sometimes a stronger bactericide?



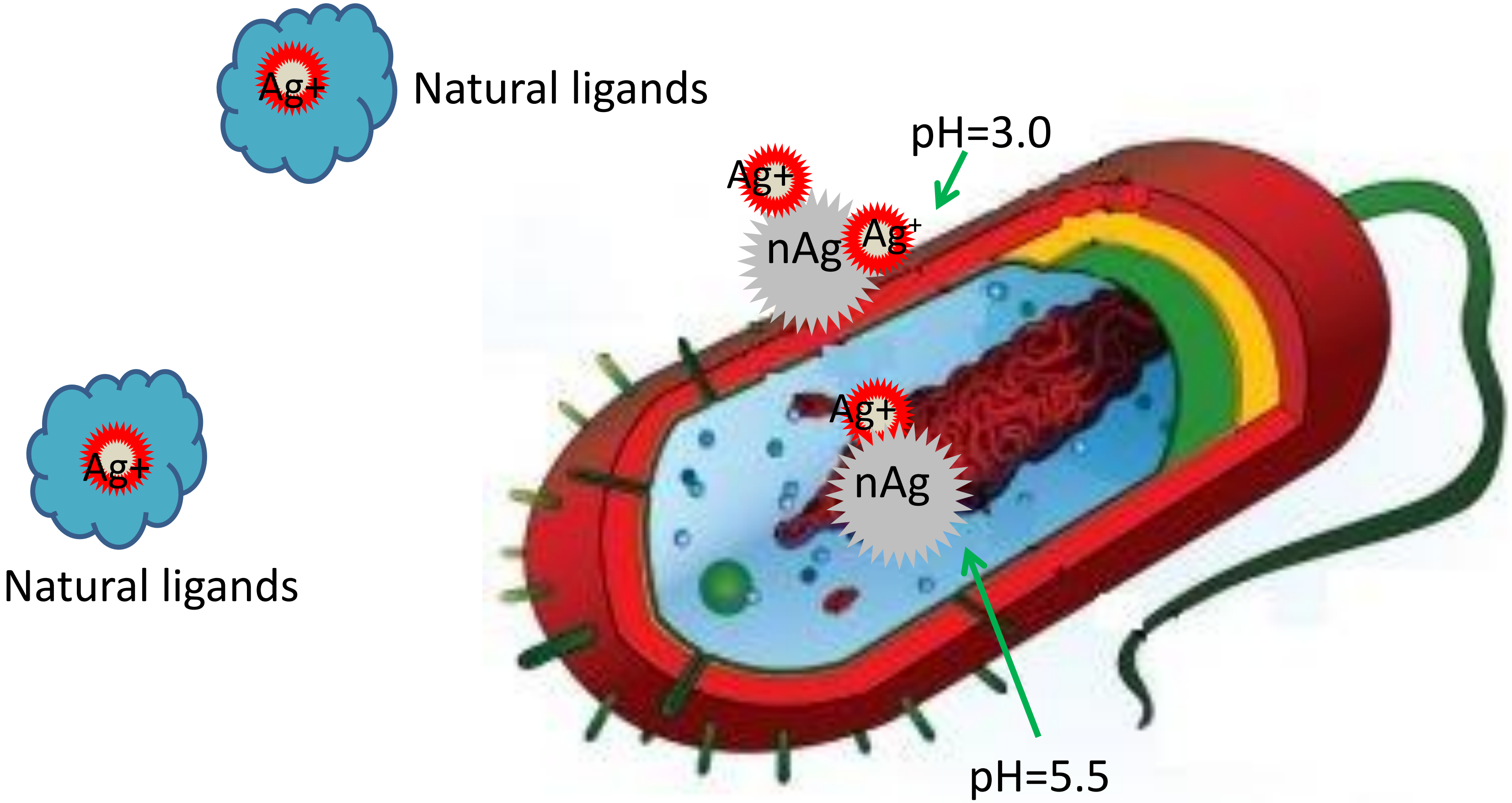
Max [Ag^+]: 3µM; [Cl^-]: 3µM



Max [nAg]: 57µM; [Cl^-]: 57µM

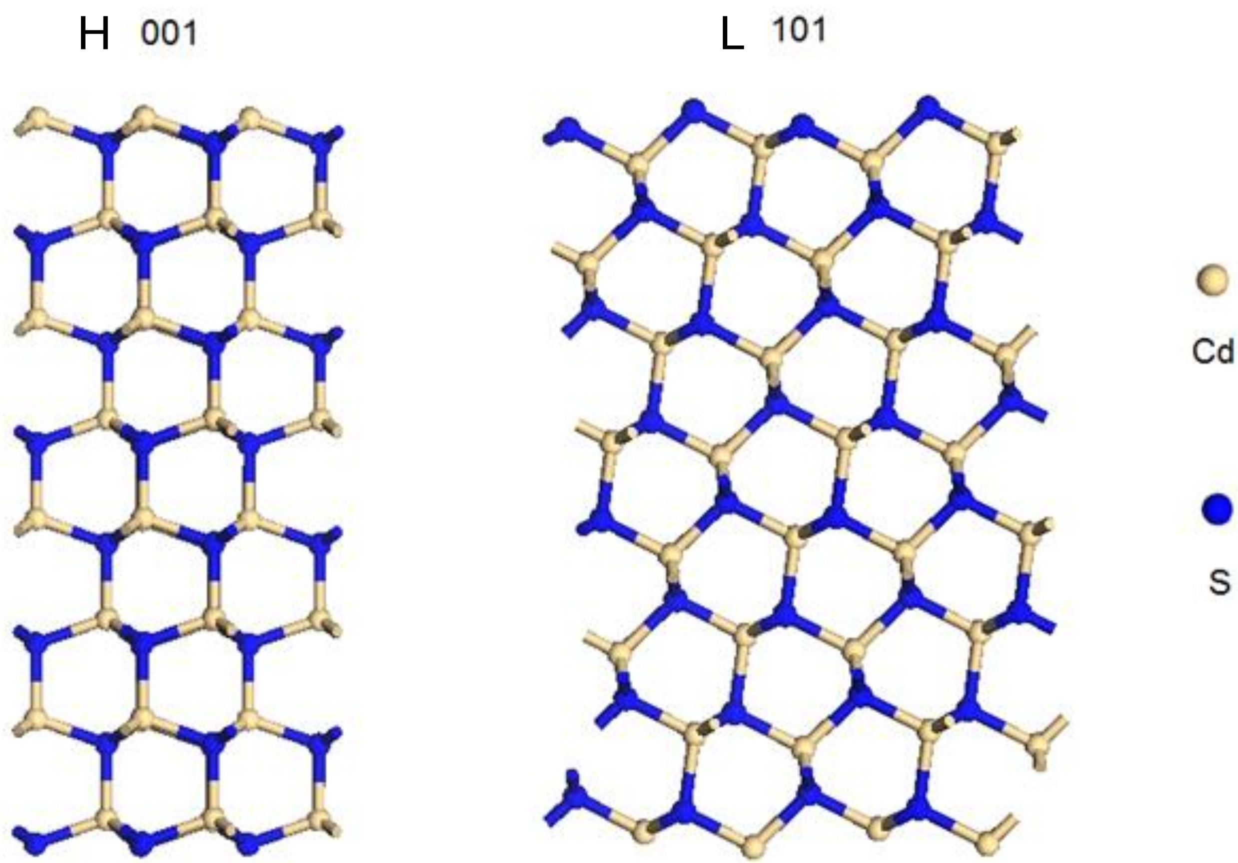
- Cl^- (& other ligands, NOM) reduce Ag^+ bioavailability and preferentially decrease its toxicity, even without precipitation
- nAg may then be more bioavailable & effectively deliver Ag^+

More Effective Delivery of Ag^+ to Membrane and Cytoplasm



How does surface energy affects NP reactivity and toxicity?

The surprising behavior of CdS nanorods



Liu L., M. Sun, Q. Li, H. Zhang, K. Yu, M. Li, C. Zhang, G. Cao, Y. Yuang. H. Zhai, W. Chen and P. Alvarez (2016). NanoLetters. 16, 688−694.

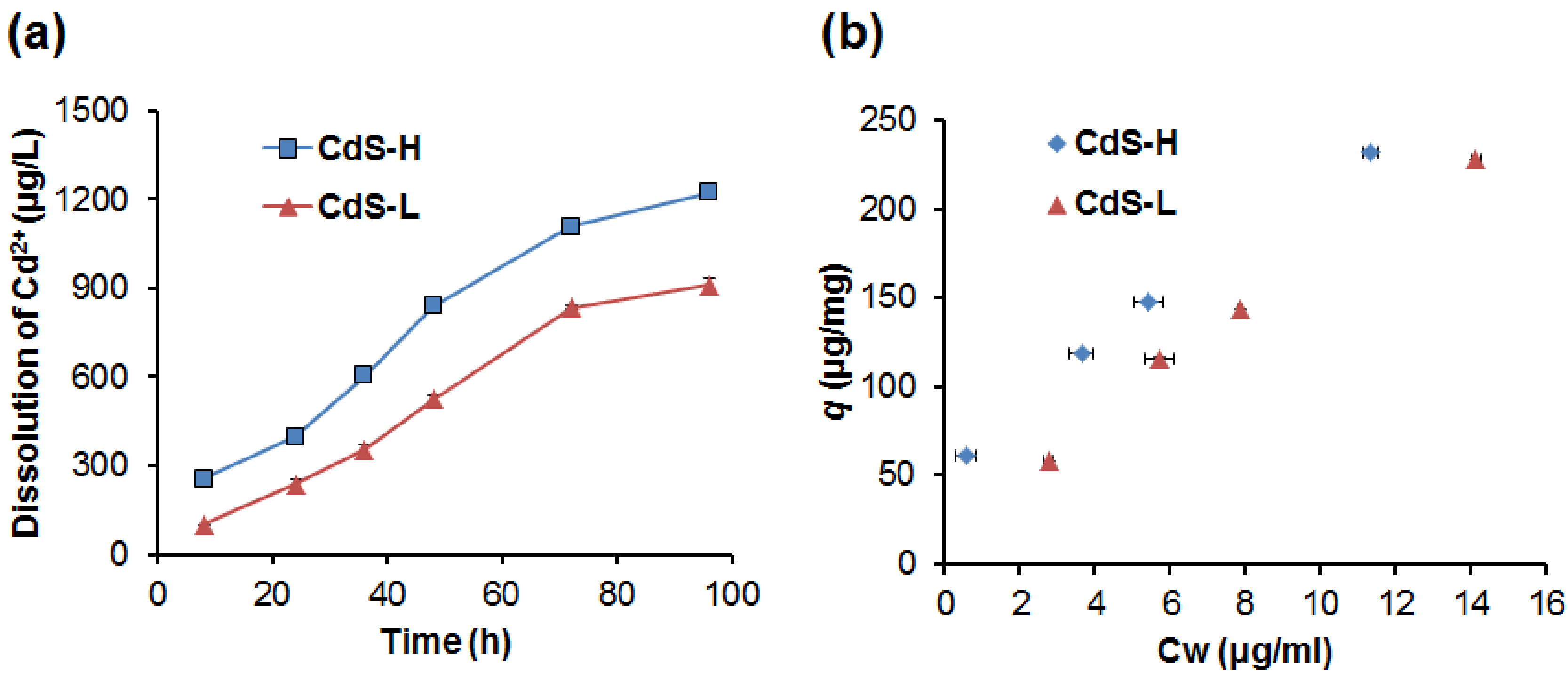
{001} facet (CdS-H) has higher surface energy than {101} facet (CdS-L)

	CdS-H	CdS-L
Length (nm)	110 ± 26	108 ± 11
Width (nm)	25 ± 3	22 ± 4
Surface energy (J/m^2)	**0.627**	0.451
Surface area (m^2/g)	42.6	49.0
ζ potential (mV)	-12.3 ± 1.6	-9.9 ± 1.2

But similar other properties (size, charge etc.)

CdS-H is more reactive:

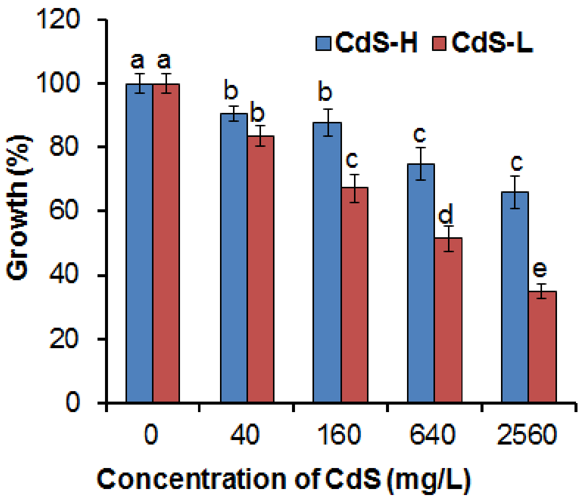
- Faster release of toxic Cd^{2+} and
- Higher tendency to associate with proteins



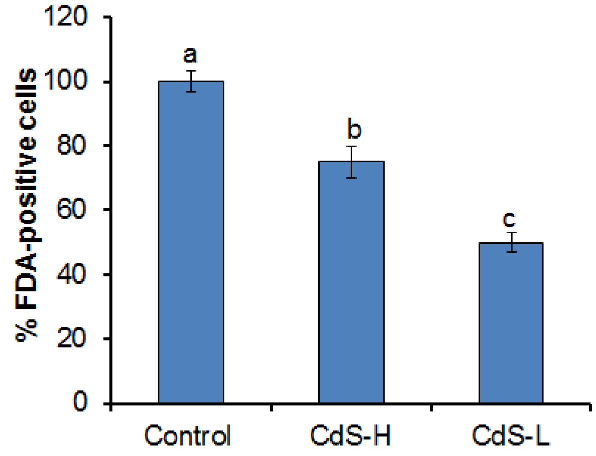
So CdS-H should be more toxic?

But CdS-L was more cytotoxic!

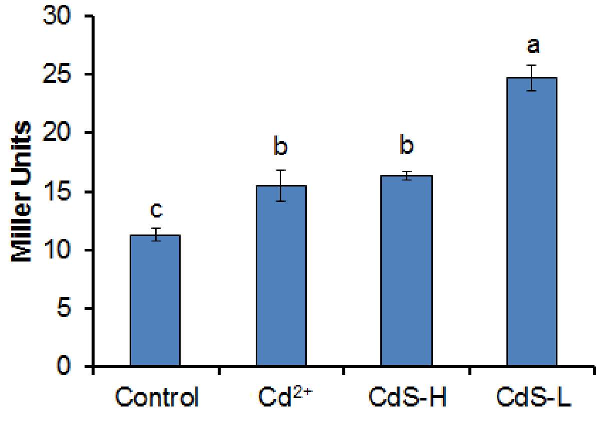
(a) Growth inhibition



(b) Cell viability

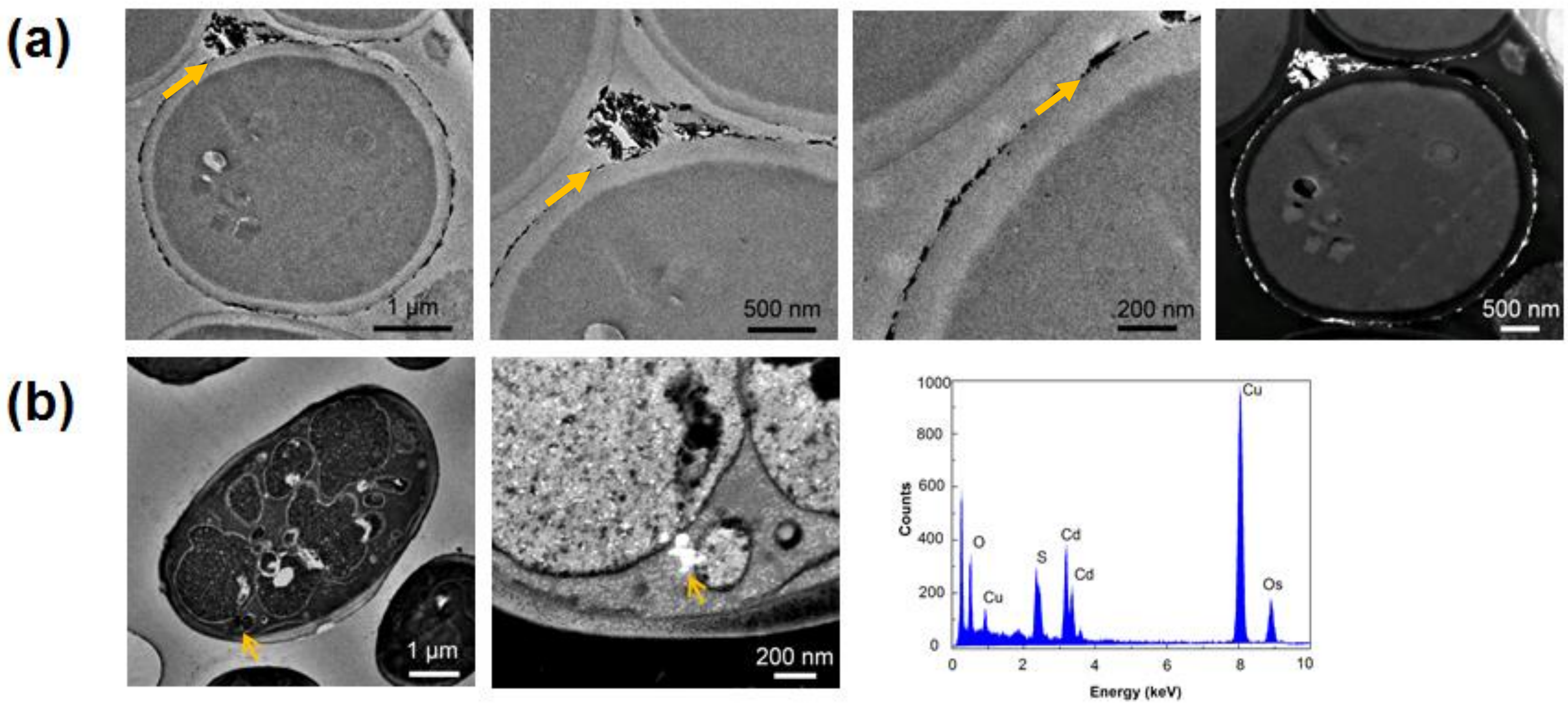


(c) ER Stress



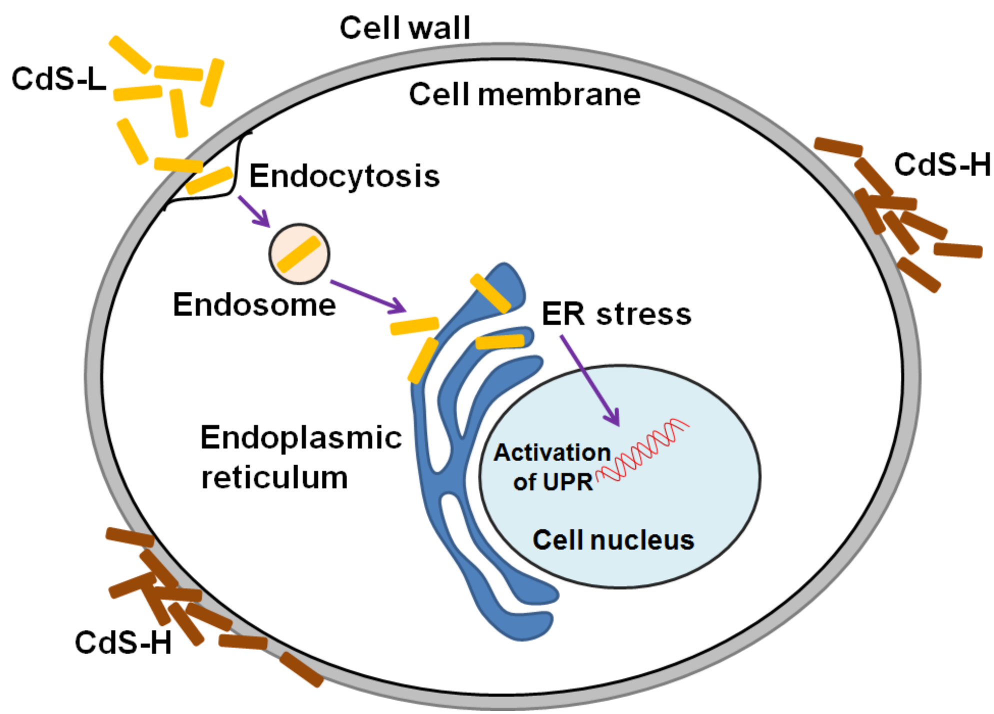
(a) Accumulation of CdS-H on cell wall.

(b) Intracellular uptake of CdS-L (confirmed by energy-dispersive X-ray spectroscopy



Summary of Effect of Surface Energy

- CdS-H was less toxic than CdS-L (despite similar morphology, aggregate size, & charge).
- CdS-H adsorbed to the yeast's cell wall, which decreased endocytosis.
- Higher uptake of CdS-L hindered cell viability and increased ER stress despite lower release of toxic Cd^{2+} ions.



Liu L., M. Sun, Q. Li, H. Zhang, K. Yu, M. Li, … W. Chen and P. Alvarez (2016). NanoLetters. 16, 688−694.

Safer Use of ENMs

Risk = Hazard x Exposure

Hazard

- Prioritize use of ENMs of benign, low-cost, and earth-abundant compositions (GRAS); Green Chemistry and Green Engineering
- Experts panel to select ENMs before incorporation into products
- Interface with TSCA in the US and REACH in the EU

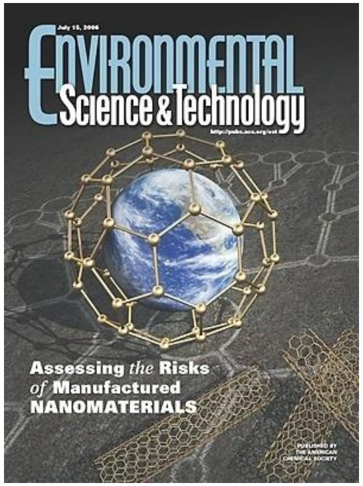
Exposure

- Immobilize ENMs to minimize release and exposure and enable reuse (no free NPs)
- Model & monitor treated water for leaching
- Foster safety in manufacturing by iterating with OSHA on best practices
- Independent certification for meeting health & safety stds.

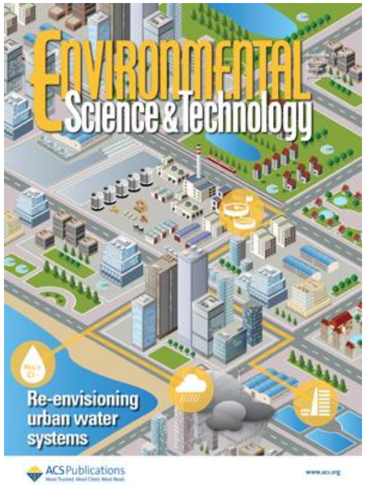
Conclusions

- Implications: Ecotoxicology-Ecosystem services (primary productivity, food webs, nutrient cycling?)

Mitigated by NOM, salts

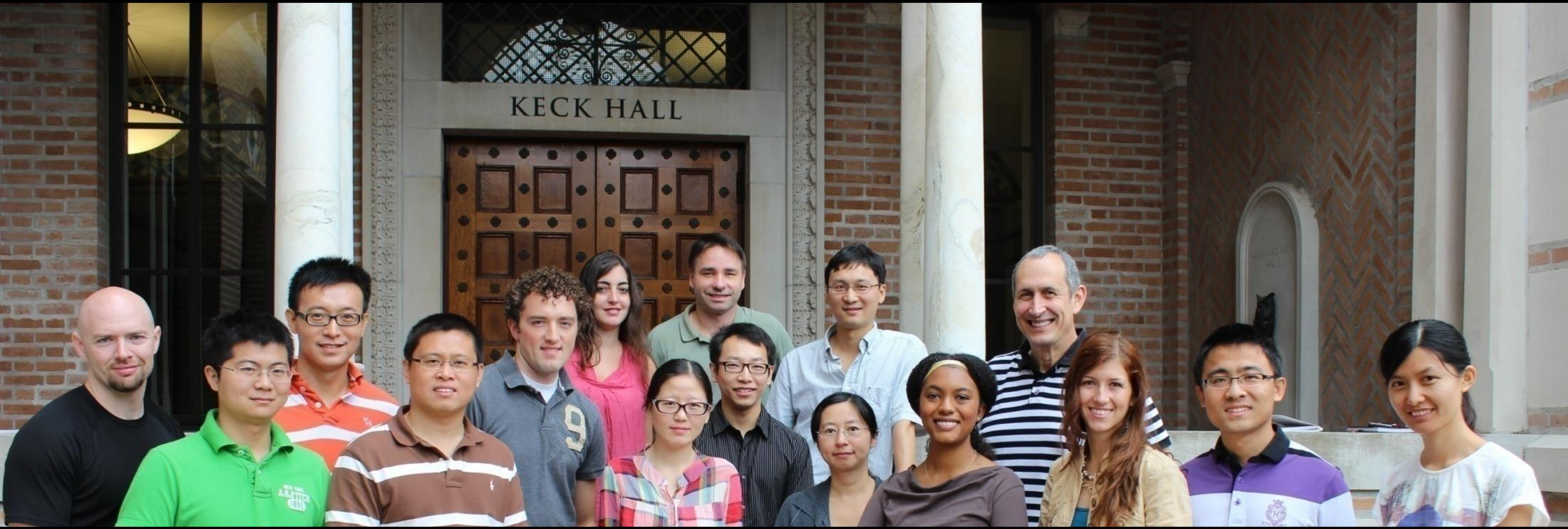


- Applications: low-energy desalination, selective adsorption and destruction of priority water pollutants, multi-functional membranes, etc.



Thanks! - Graduate Students and Postdocs

NSF



Ph.D. M. Vermace; Craig Hunt; Marcio da Silva; Nanh Lovanh; Alethia Vazquez; Roopa Kamath; Michal Rysz; Natalie Capiro; Delina Lyon; Rosa Dominguez, Dong Li; Diego Gomez, Jacques Mathieu, Leti Vega, Xiaolei Qu, **Jon Brame,** Jiawei Ma, Pinfeng Yu, Mengyan Li, Jing Wang, Ana McPhail, O. Monzon

M.S.E. Gary Chesley; Sang-Chong Lieu; Pete Svebakken; Phil Kovacs; Rod Christensen; Marc Roehl; Ken Rotert; Brad Helland; Leslie Cronkhite; Annette Dietz; Bill Schnabel; Ed Ruppenkamp; Leslie Foster; Bryan Till; Nahide Gulensoy; Rebecca Costura; Matt Wildman; Chad Laucamp; Todd Dejournet; Sascha Richter; Sara Kelley; Eric Sawvel; Jennifer Ginner; Sumeet Gandhi; Richard Keller; Jennifer Wojcik; Anitha Dasappa; Leslie Sherburne; Brett Sutton; Russ Sawvel; Andrea Kalafut; Roque Sanchez; Amy Monier; Isabel Raciny; **Katherine Zodrow**; Rachel Carlson; Robert O'Callaham; Bill Mansfield

Postdocs Graciela Ruiz; Jose Fernandez; Byung-Taek Oh; D. Kim; Joshua Shrout; Laura Adams, Sufia Kafy; Lena Brunet; **Jaesang Lee**, Jiawei Chen; Shaily Mahendra; **Zongming Xiu; Yu Yang**

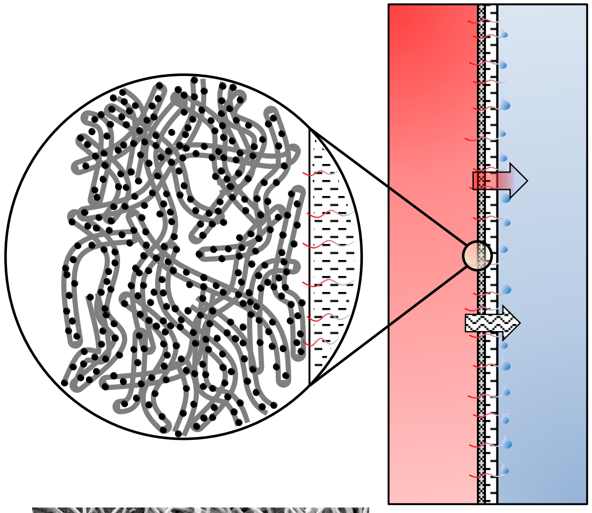
Any Questions?

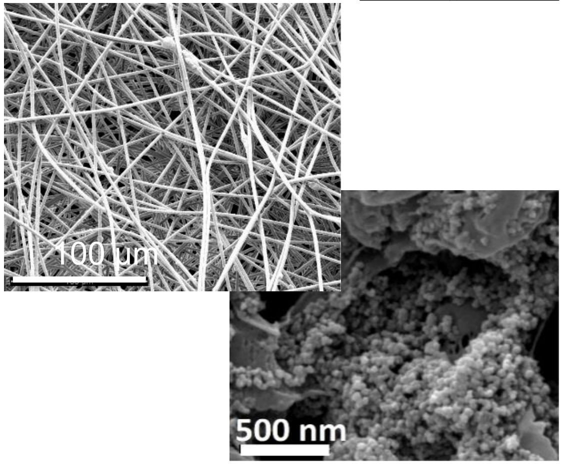
High- Level Research Questions

- How should we use novel nano-scale properties for water purification in a safe and efficient manner?
  (Use benign ENMs & immobilize them)

- How can nanomaterials be attached to surfaces or embedded into scaffolding without losing their functionality?

- How can we harness solar energy directly to reduce costs of water purification?





Potential applications for solar MD

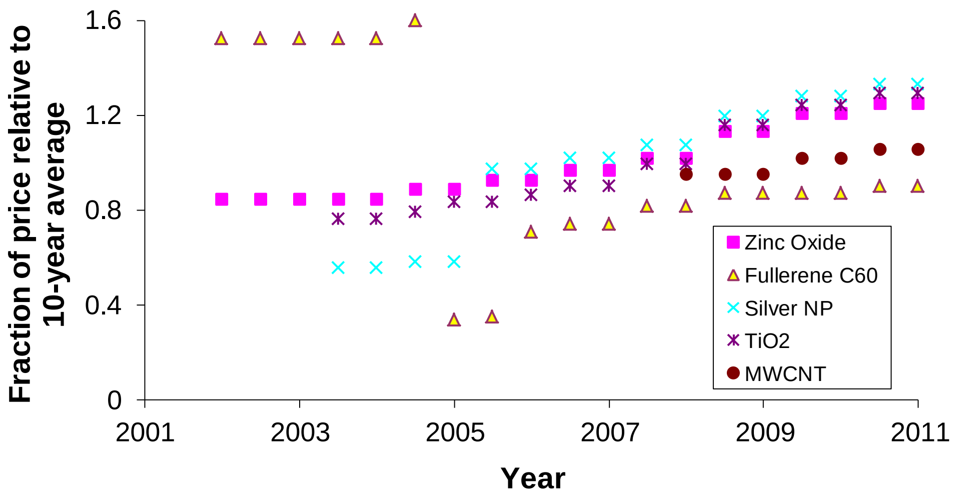
- **Off-Grid drinking water treatment**
  - Portable outdoor treatment units (e.g., camping, peace keeping)
  - Single family water purification
  - Commercial drinking water vending station for off-grid communities (solar water station)

Similar to solar charging station, could build a solar water station

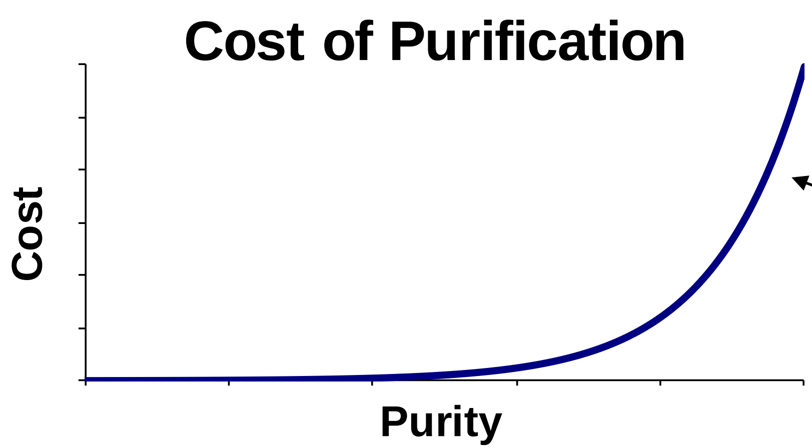
- **Industrial water treatment**
  - Reverse osmosis concentrate treatment
  - Hypersaline wastewater that cannot be handled by reverse osmosis

RO concentrate treatment

Need market-driven decrease ENM price



Few commercial applications
= low supply
→ prices stay high



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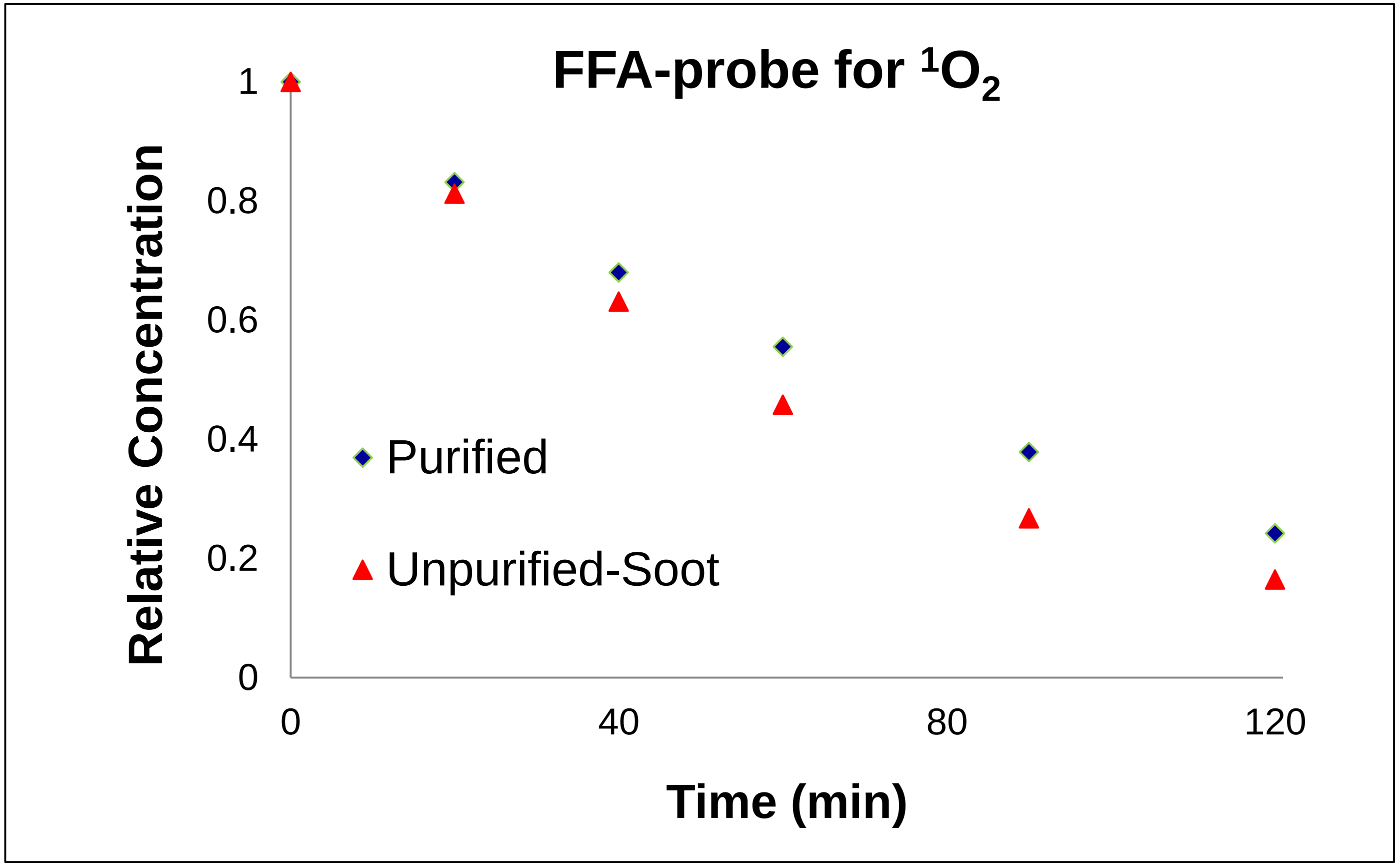
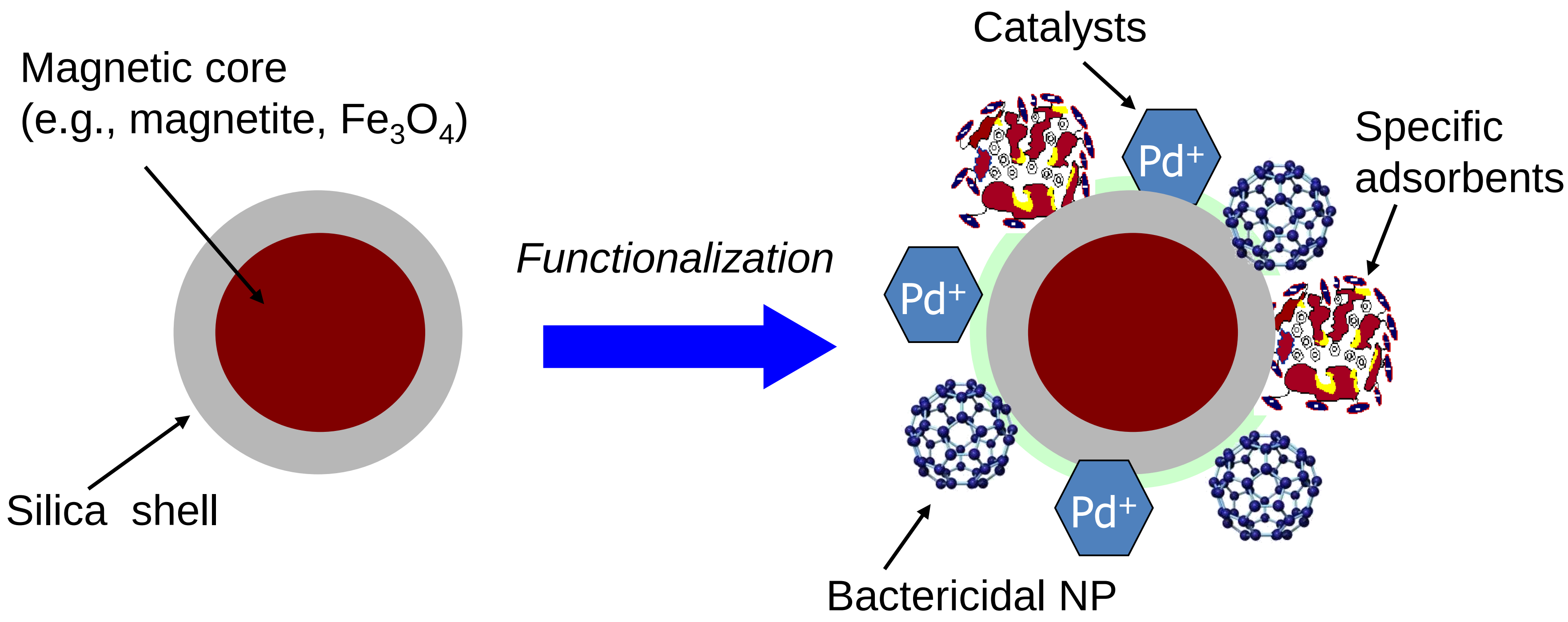
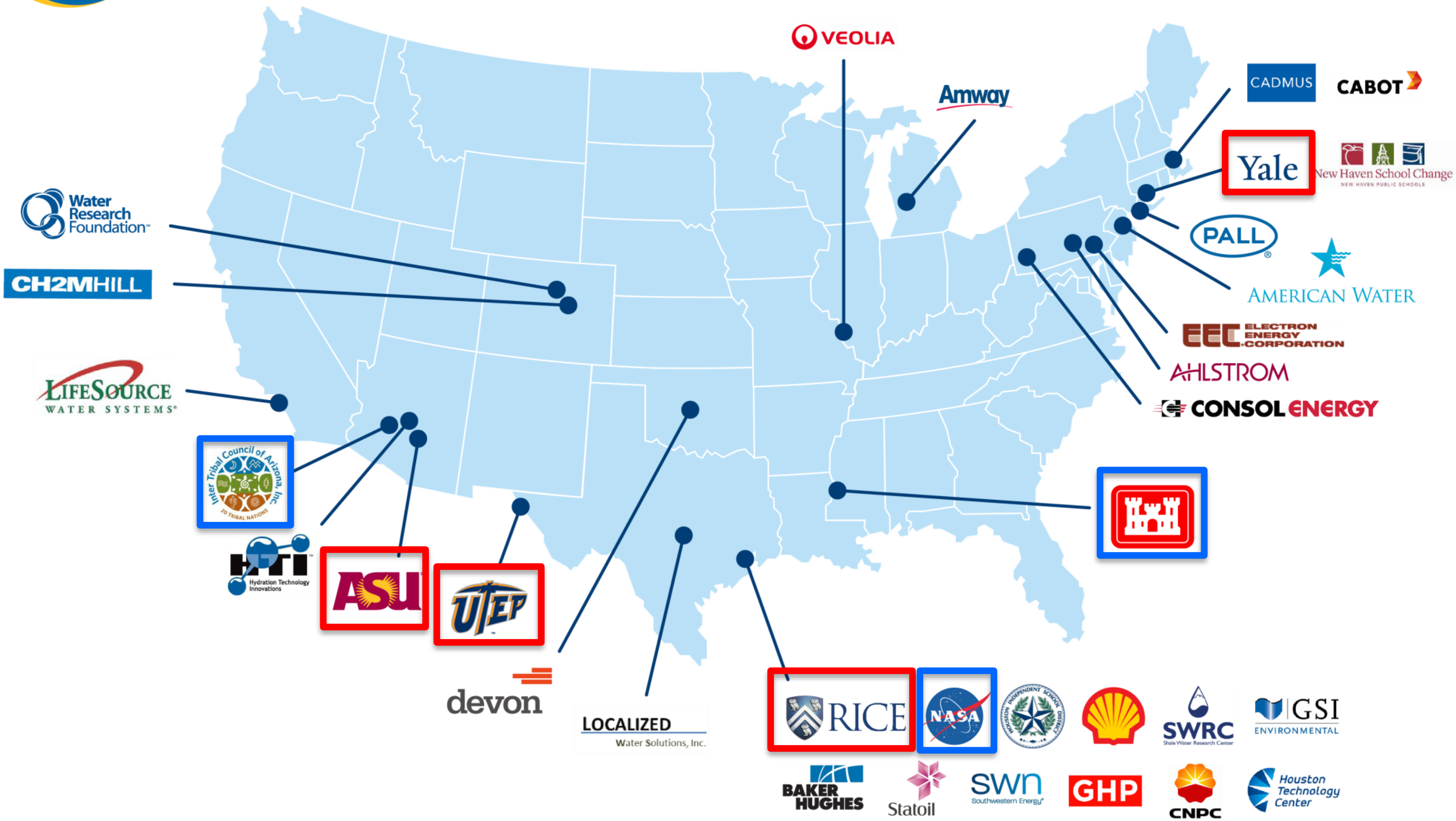


Enabling Technology
Multifunctional nanosorbents

Selective removal of target contaminants by functionalized nanoparticles supported in macroscale structures or subject to (low-energy) magnetic separation for enhanced removal kinetics & reuse

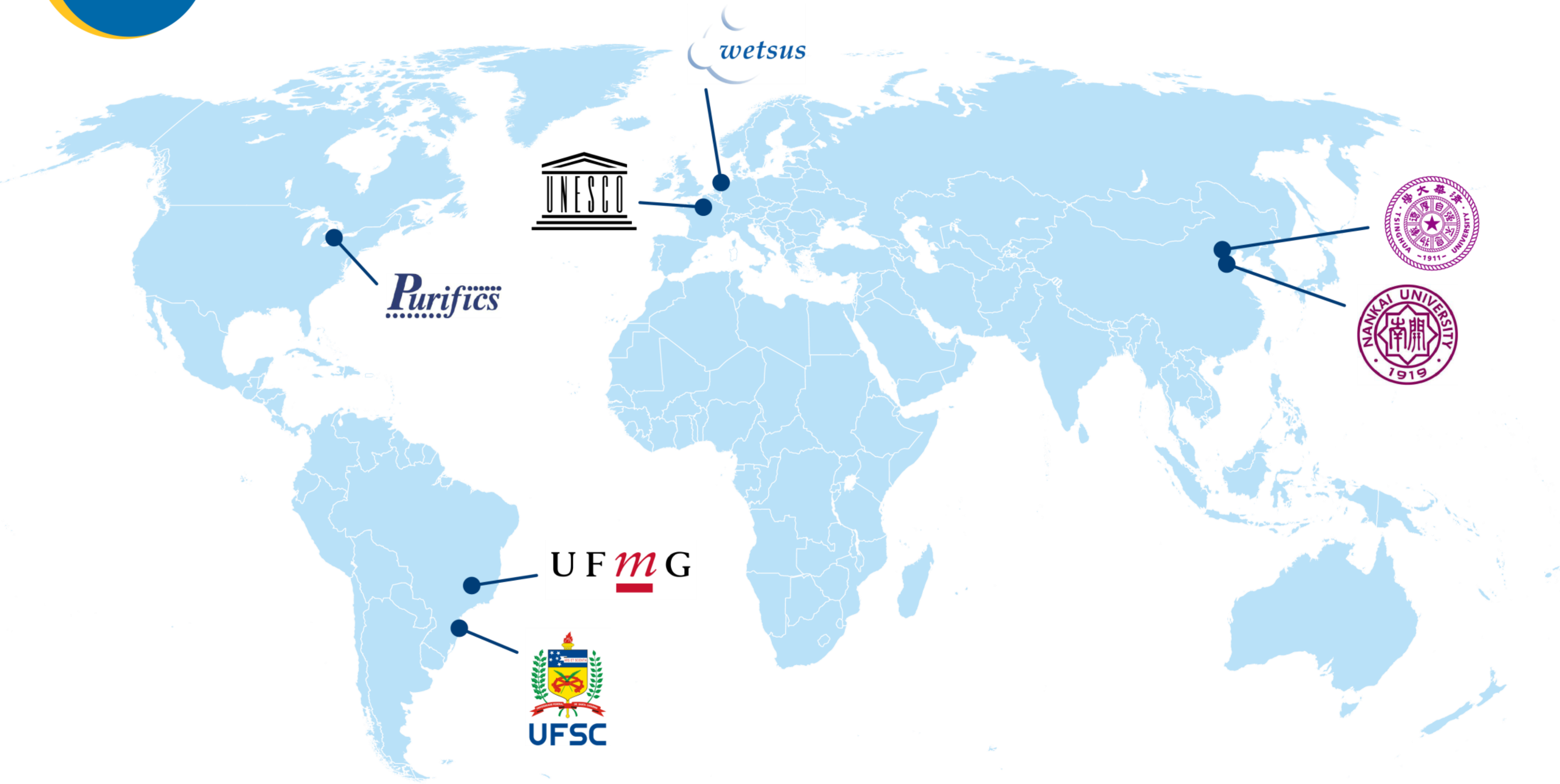


Some of Our NEWT Partners



- Innovation across value chain (nanomaterial and equipment manufacturers, service providers, R&D and deployment partners, and users)

International Partners

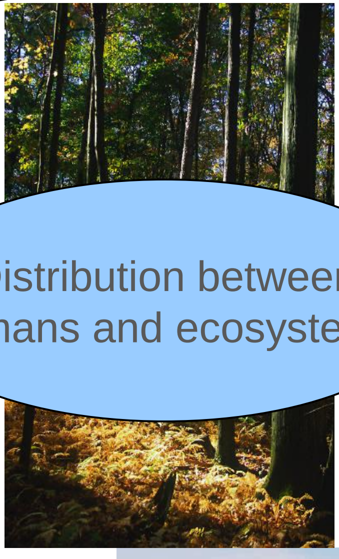


- Co-development and production of advanced multifunctional materials
- Globally-relevant research and education experiences for students
- Testbed sites for applications in fast-growing water markets

7 Grand Challenges Related to Water

Safe water quality for a growing population

Water infrastructure (distribution & collection)



Distribution between humans and ecosystems

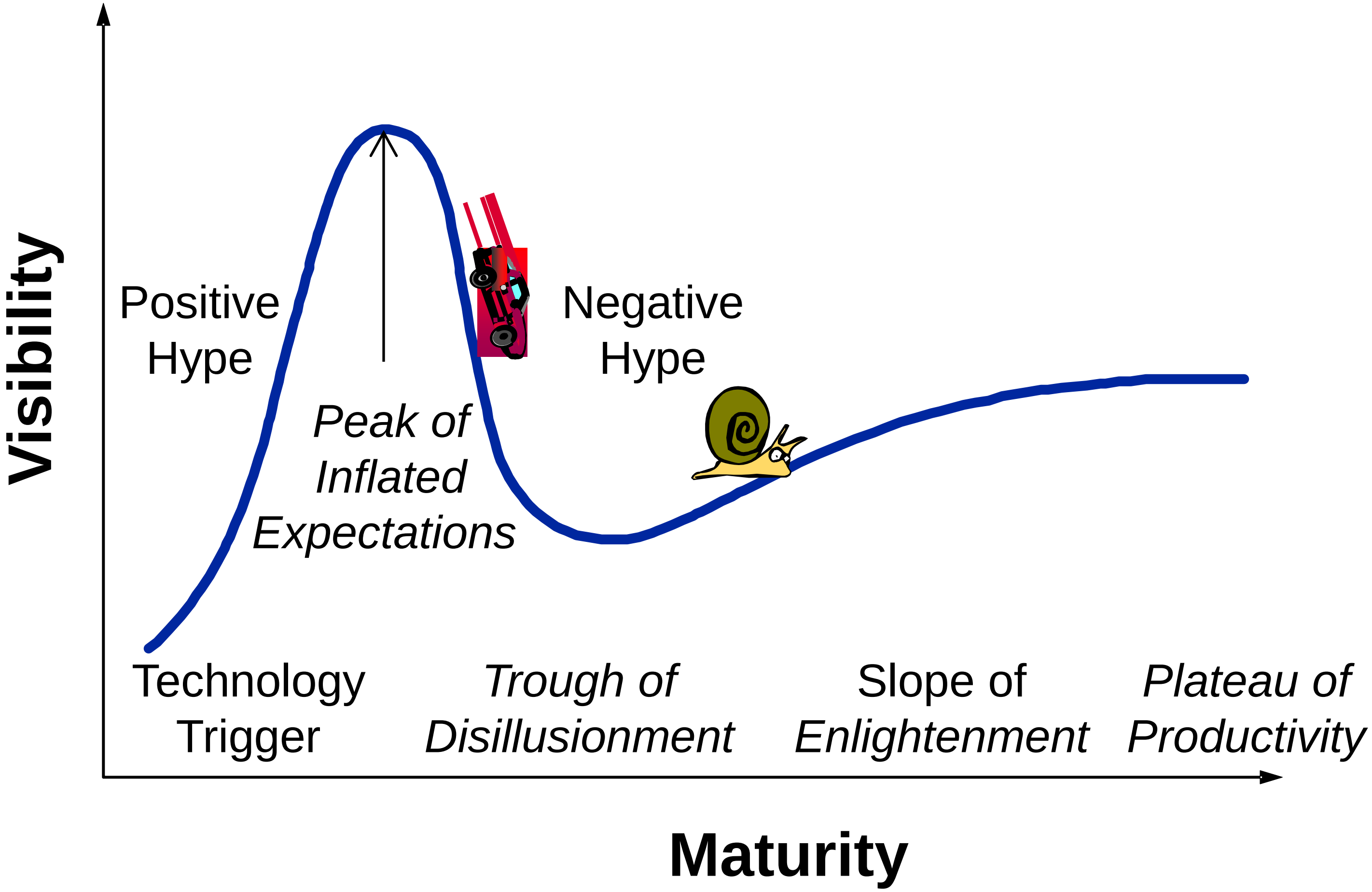
Water induced disasters and flood protection

Enough food for all

Water to produce energy

Solution for water conflicts and fair water share for all

Quo Vadis, Nano?

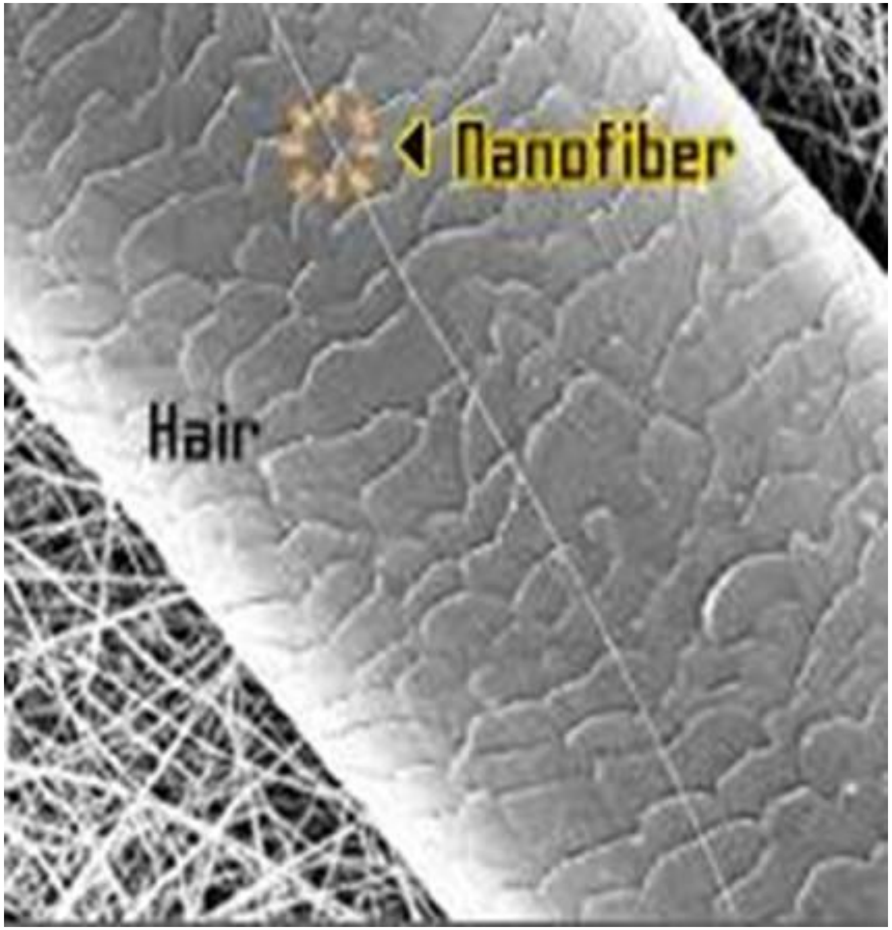


"Nanohype" - Berube

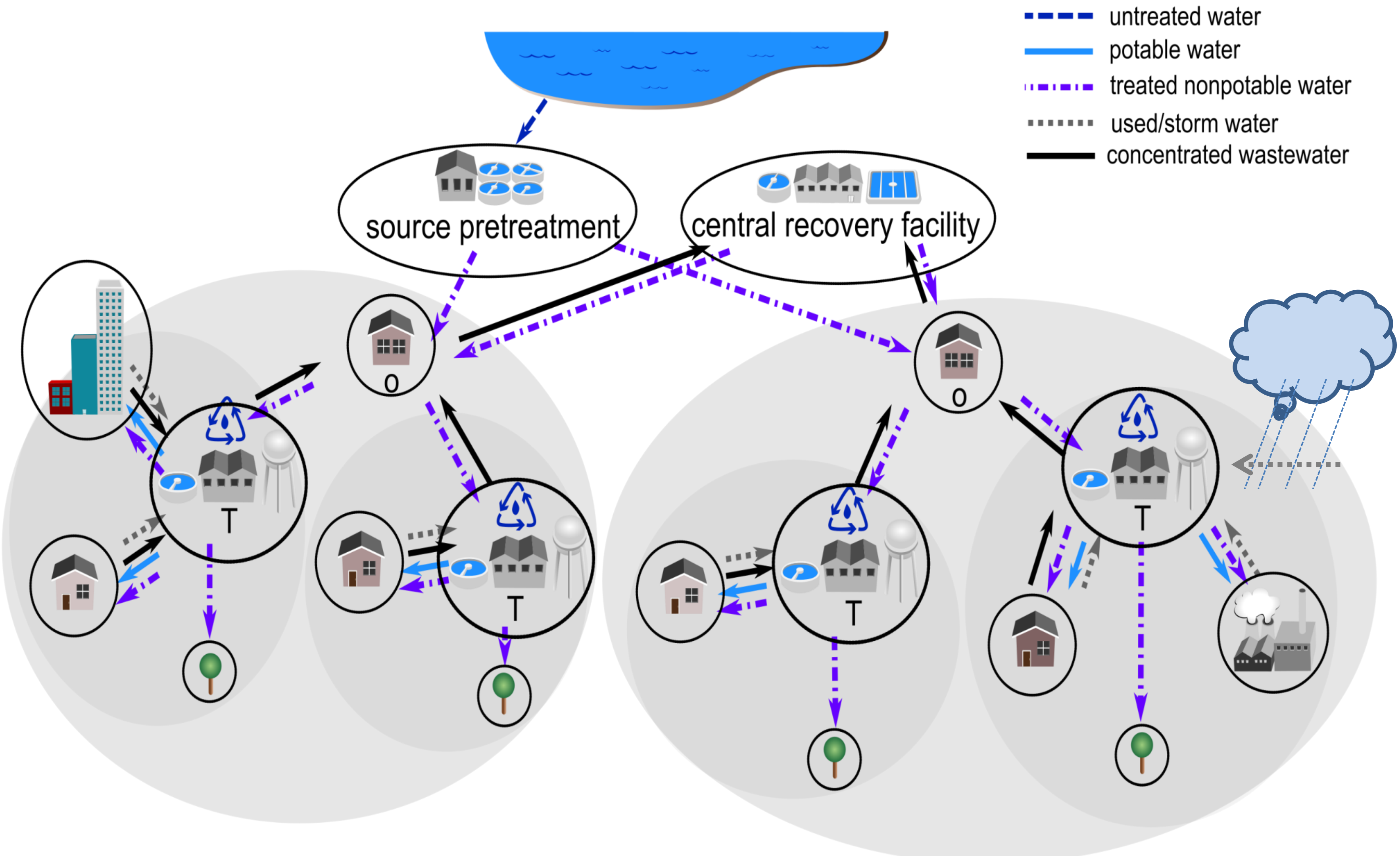
Nano = Dwarf (Greek) = 10^{-9}

"Nanotechnology is the understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications."

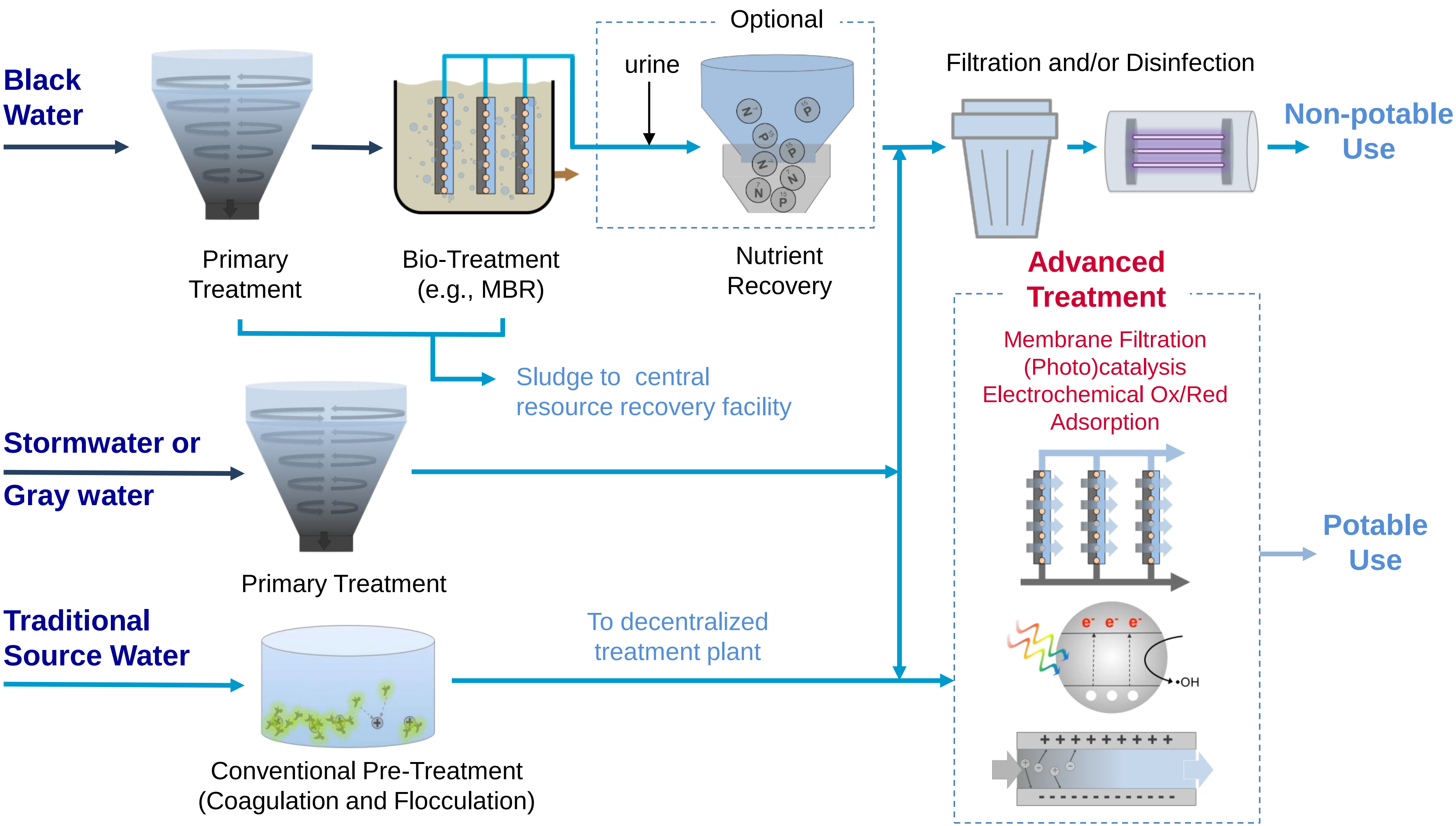
-National Nanotechnology Initiative



Flows of “fit-for purpose” water in an integrated water management system



Modular Treatment System at Decentralized Facilities that Integrate Various Sources



Houston: 4th largest city in USA
"Energy Capital" of the world

RICE UNIVERSITY

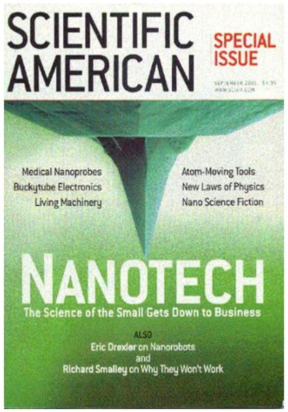
- 3879 undergraduate & 2861 graduate students (6:1 student to faculty ratio)
- Small, but highly ranked
  - USNEWS ranks it #15 overall (highest-ranked in Texas 2017)
  - Leiden ranking (2013): #1 in the world in natural sciences and engineering for the quality and impact of its scientific publications
  - Princeton Review: #1 for best quality of life

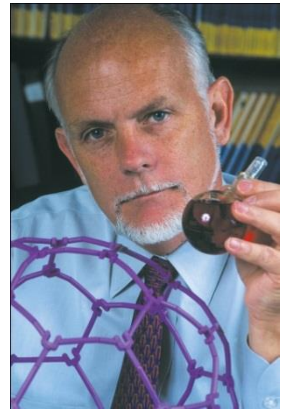
Rice University - Texas Medical Center

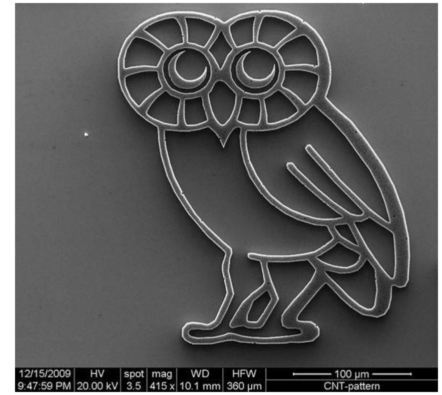
Rice is part of the world's largest medical complex:

Strong Tradition in Bioscience Research

Rice: A First Mover in Nanotechnology







- Ranked among top nanotechnology programs in the world
- The first university-sponsored nanotechnology effort (1994!)
- Nobel prize awarded in 1996 for discovery of C_{60}
- CBEN (2001) was one of the 1st national nanotechnology centers
- Rice faculty are leaders in carbon nanotechnology, nanomedicine, nanophotonics, and environmental nanotechnology

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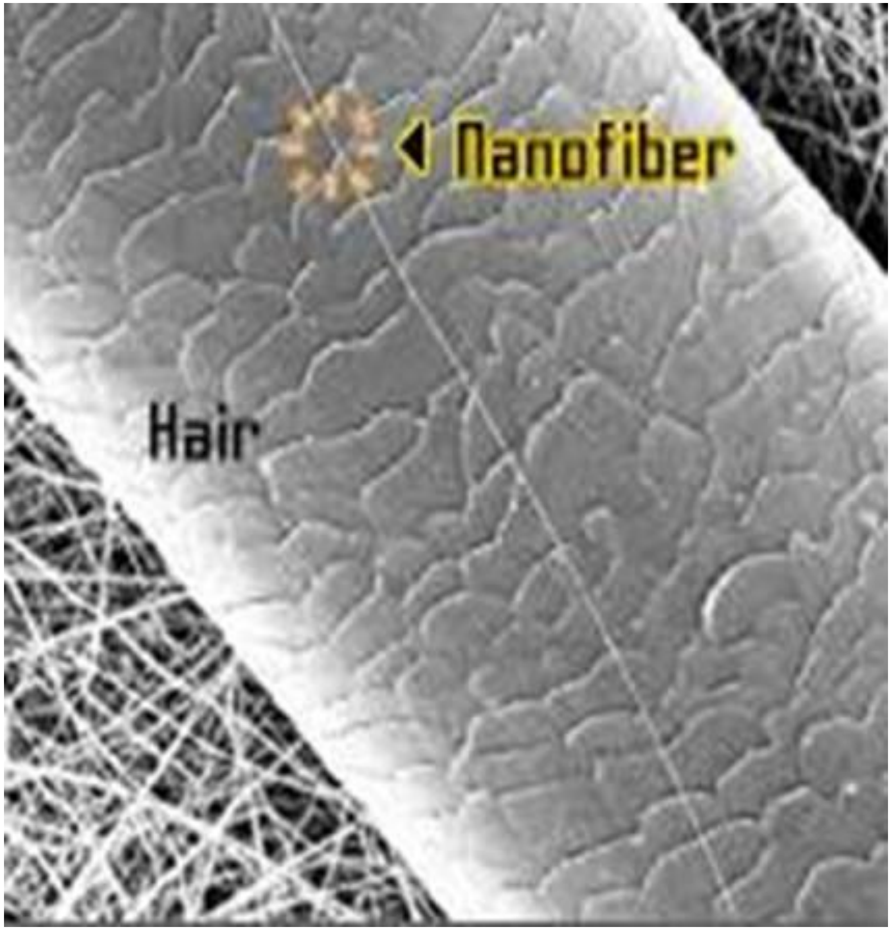
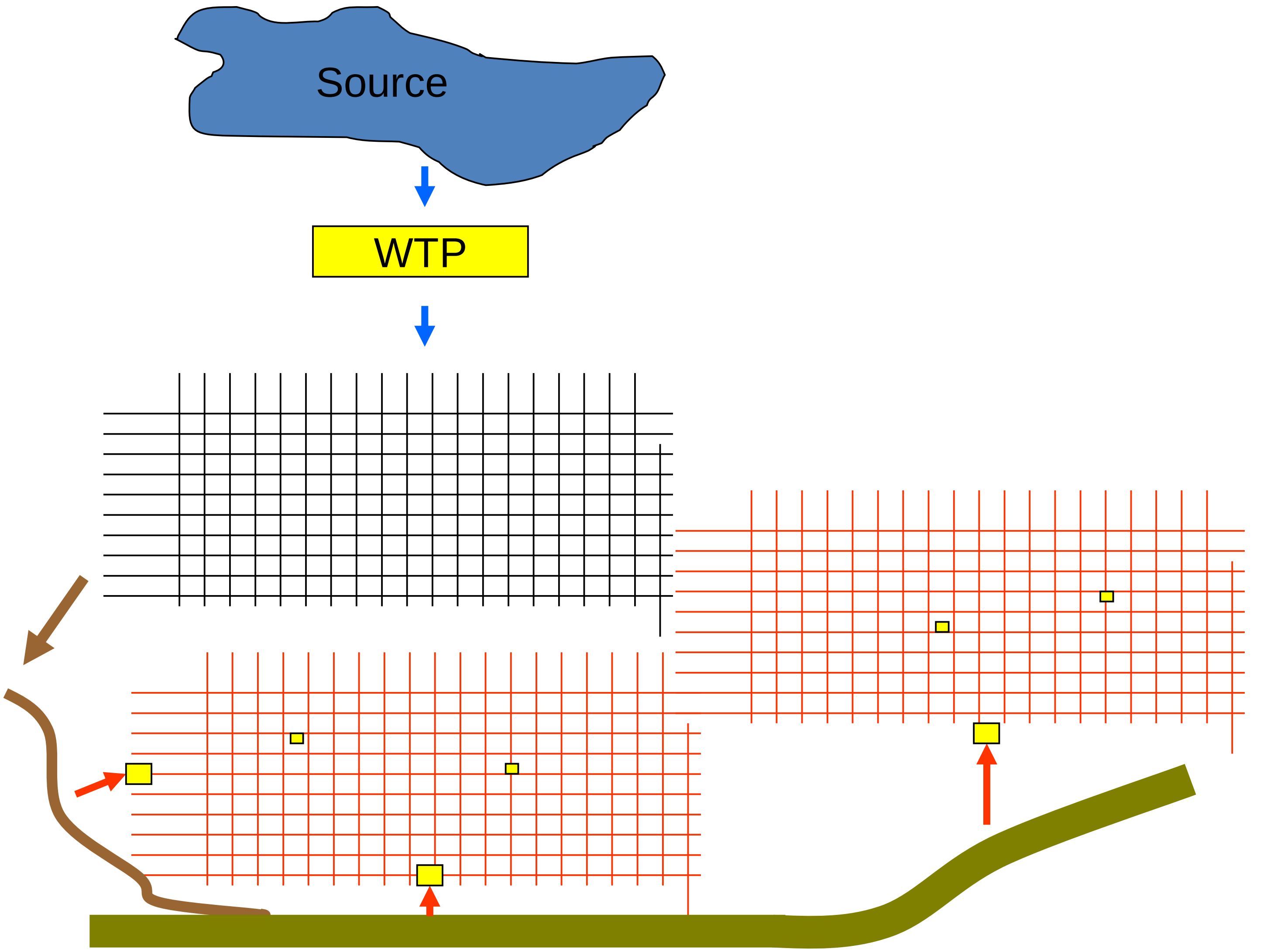




Integrate potable water, storm water, and wastewater systems and *(fit-for-purpose) distributed treatment facilities* to minimize freshwater withdrawal and energy consumption for transporting water

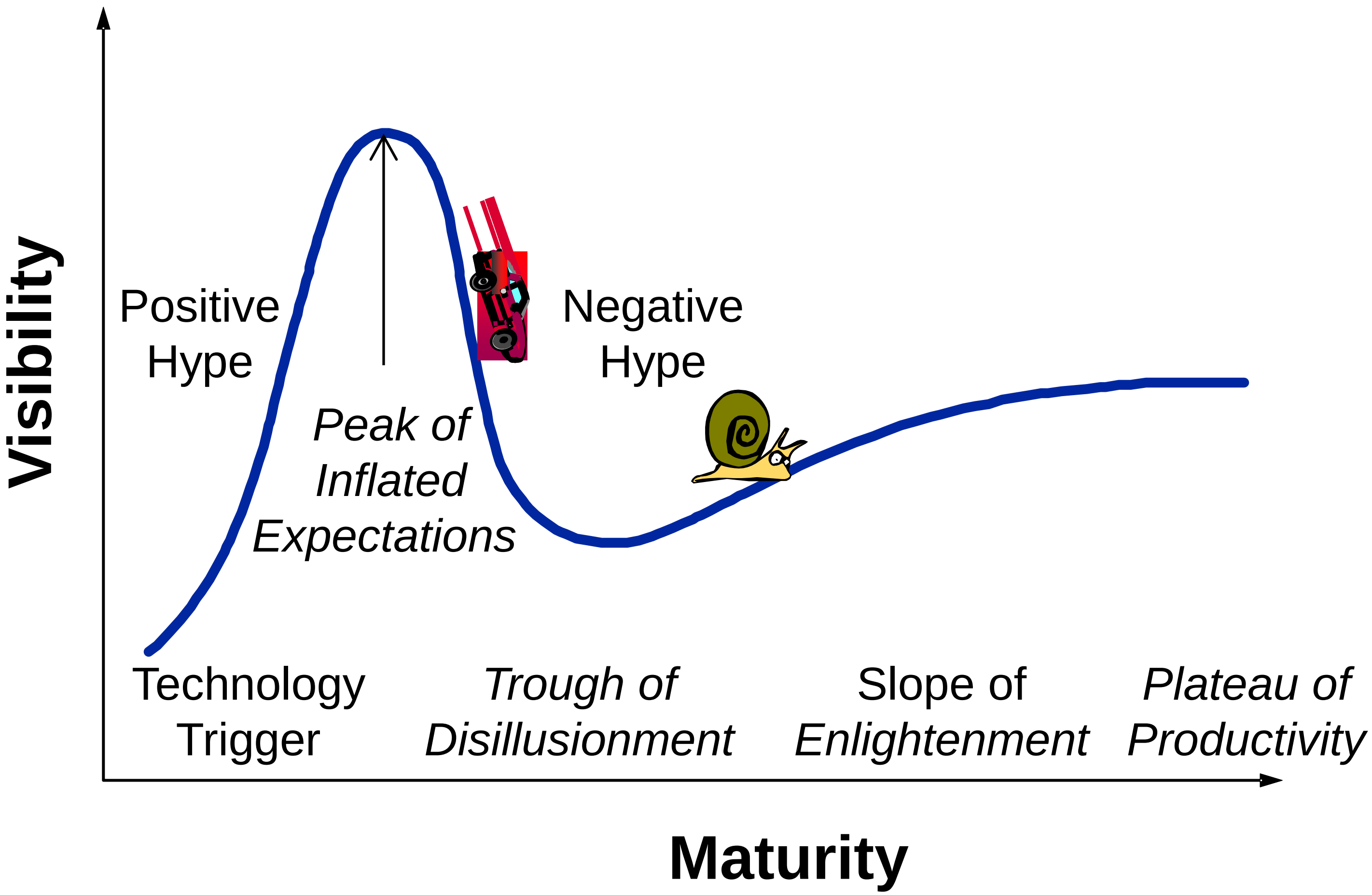
Drivers for Decentralized (Distributed) Modular Treatment

- Lack of adequate infrastructure (distribution systems, electricity)
- Match water supply with consumer location (avoid contamination during transport & storage)
- Reduce water losses and headloss in large and complex distribution systems (saves energy!)
- Use networks of ***both*** centralized & decentralized treatment to supplement supply with reclaimed water
- Differential treatment to match treated water quality to the intended use, lowering treatment cost

Opportunities for Engineered Nanomaterials (ENMs) in Water Treatment and Reuse

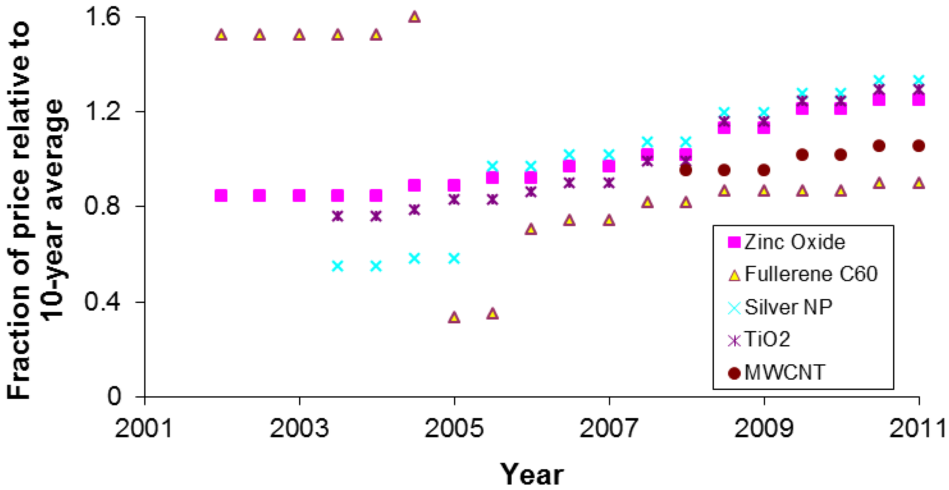
ENM Properties	***Examples of Enabled Technologies***
Large surface area to volume ratio	Superior sorbents (e.g., nanomagnetite or graphene oxides to remove heavy metals and radionuclides)
Enhanced catalytic properties	Hypercatalysts for advanced oxidation (TiO_2 & fullerene-based photocatalysts) & reduction processes (Pd/Au)
Antimicrobial properties	Disinfection and biofouling control without harmful byproducts
Multi-functionality (antibiotic, catalytic)	Fouling-resistant (self-cleaning and self-repairing) filtration membranes that operate with less energy
Self-assembly on surfaces	Surface structures and nanopatterns that decrease bacterial adhesion, biofouling, and corrosion
High conductivity	Novel electrodes for capacitive deionization (electro-sorption) and energy-efficient desalination
Fluorescence	Sensitive sensors to detect pathogens, priority pollutants

Quo Vadis, Nano?



“Nanohype” - Berube

Need market-driven decrease ENM price



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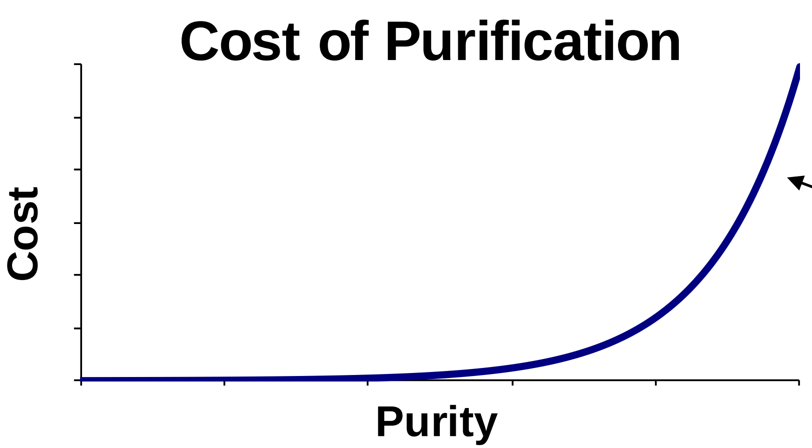

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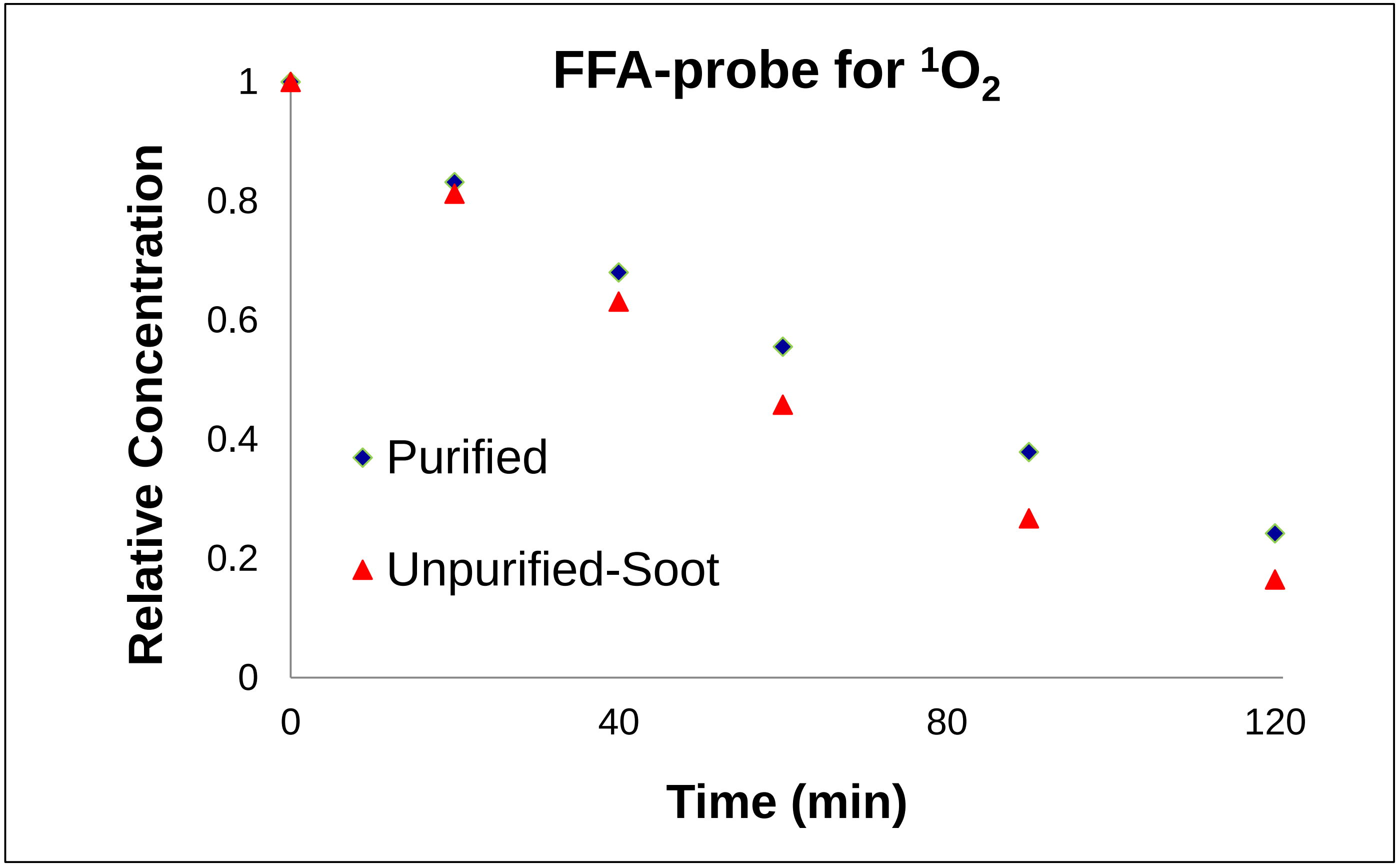
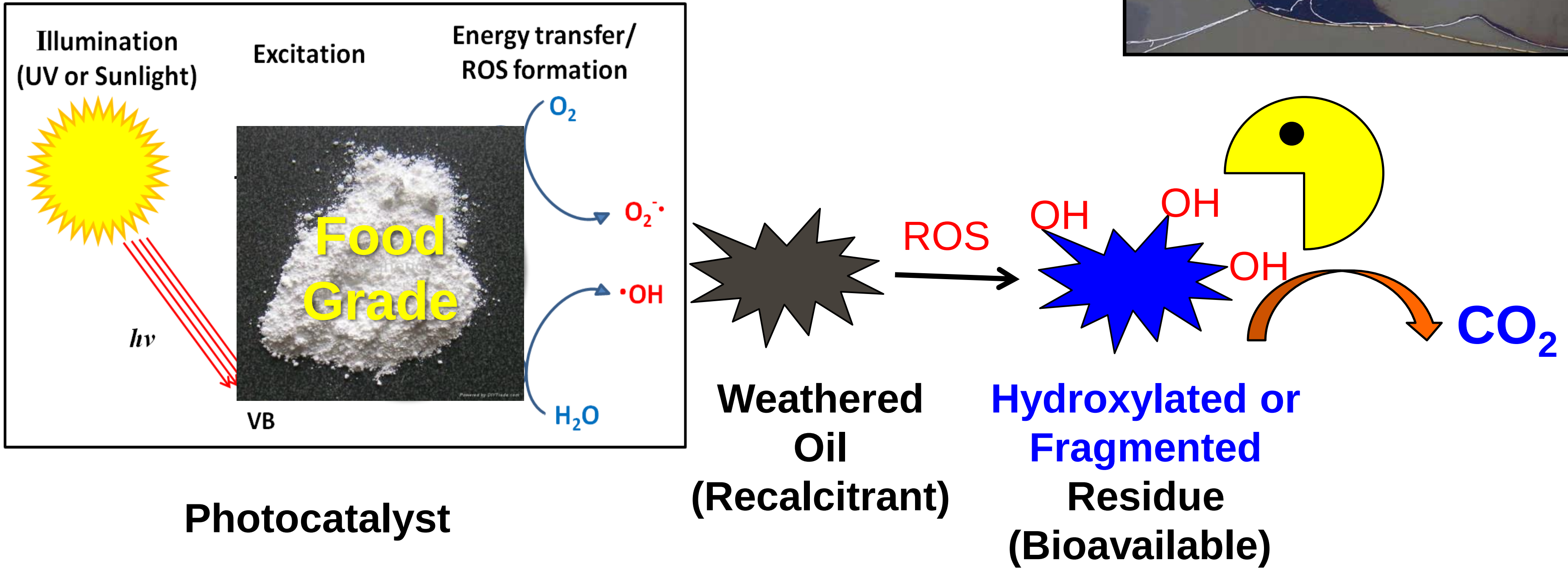
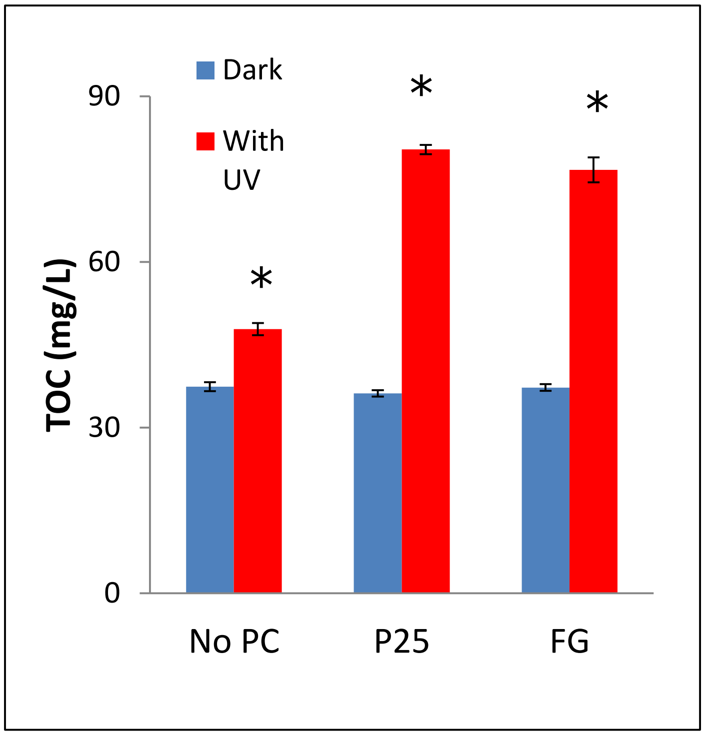
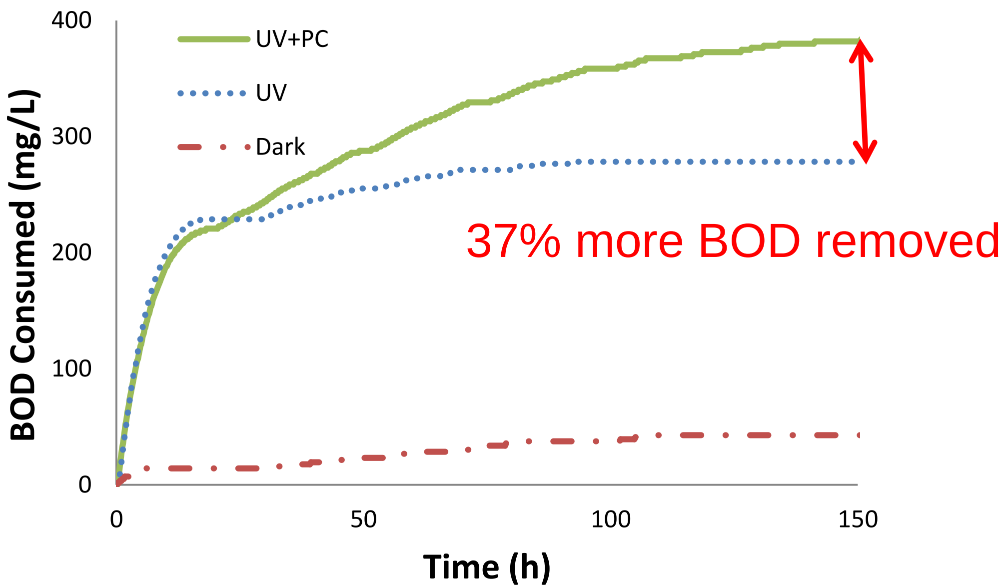


Photocatalytic Hydroxylation of Weathered Oil to Enhance Bioavailability and Bioremediation



Photocatalysis Increased Solubilization and Biodegradation of Weathered Oil

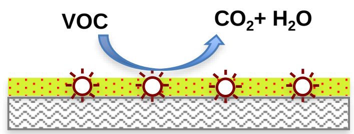


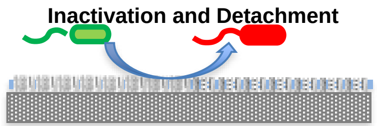


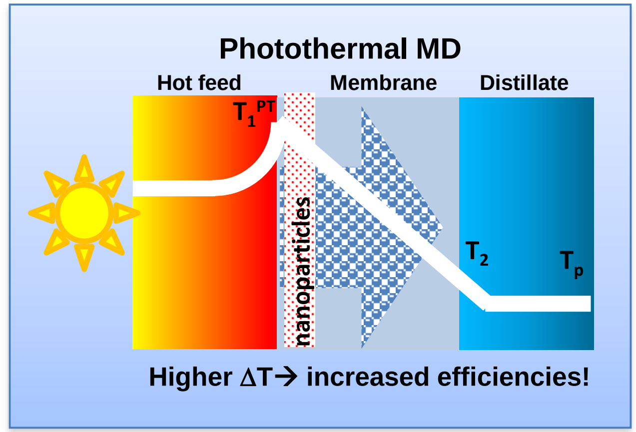
* statistically significant (*p* <0.05) after 1-day exposure

Brame J., S.W. Hong, J. Lee and P.J.J. Alvarez (2013). *Chemosphere* 90: 2315–2319.

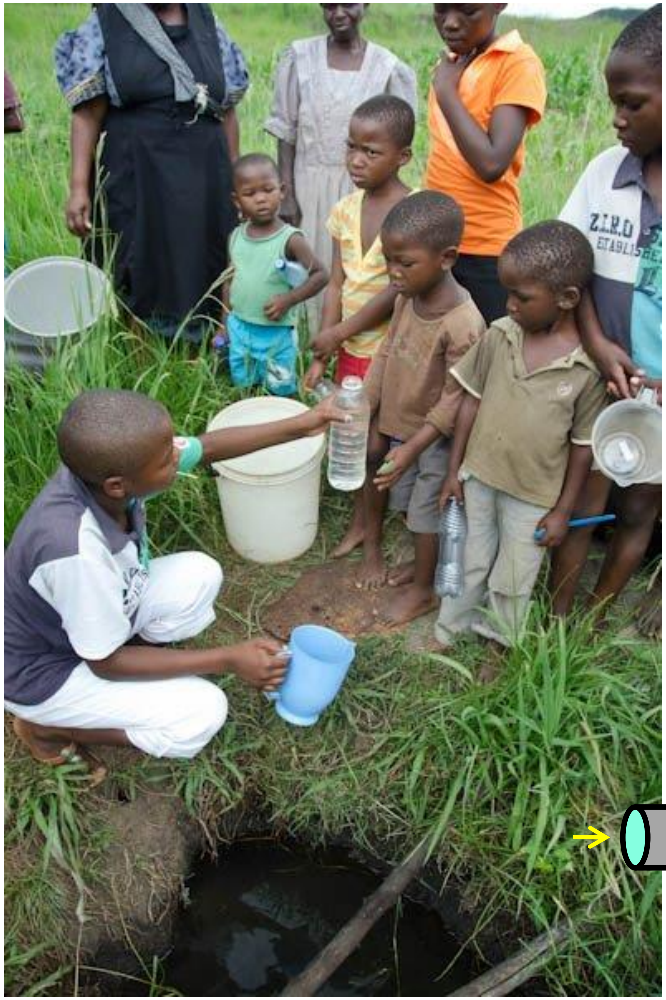
	Multifunctional coating	High performance base membrane	Novel condensation surface
Membrane material development	Photocatalytic degradation of VOC (1.3, 3.3); Anti- fouling/scaling (3.3); Photothermal activity (2.2)	High porosity, super-hydrophobicity, low thermal conductivity (2.2)	Novel biomimetic materials (e.g., desert beetles) (potential seed)
Basic science	NP/polymer interface (1.1, 2.3)	Effect of Surface property on scaling and vapor condensation (2.2, 3.1)	NP-photon interaction (2.1)
Reactor design	Light harvesting (2.4)	Low cost, light weight membrane module (2.2)	Heat recovery (NEWTSkid)

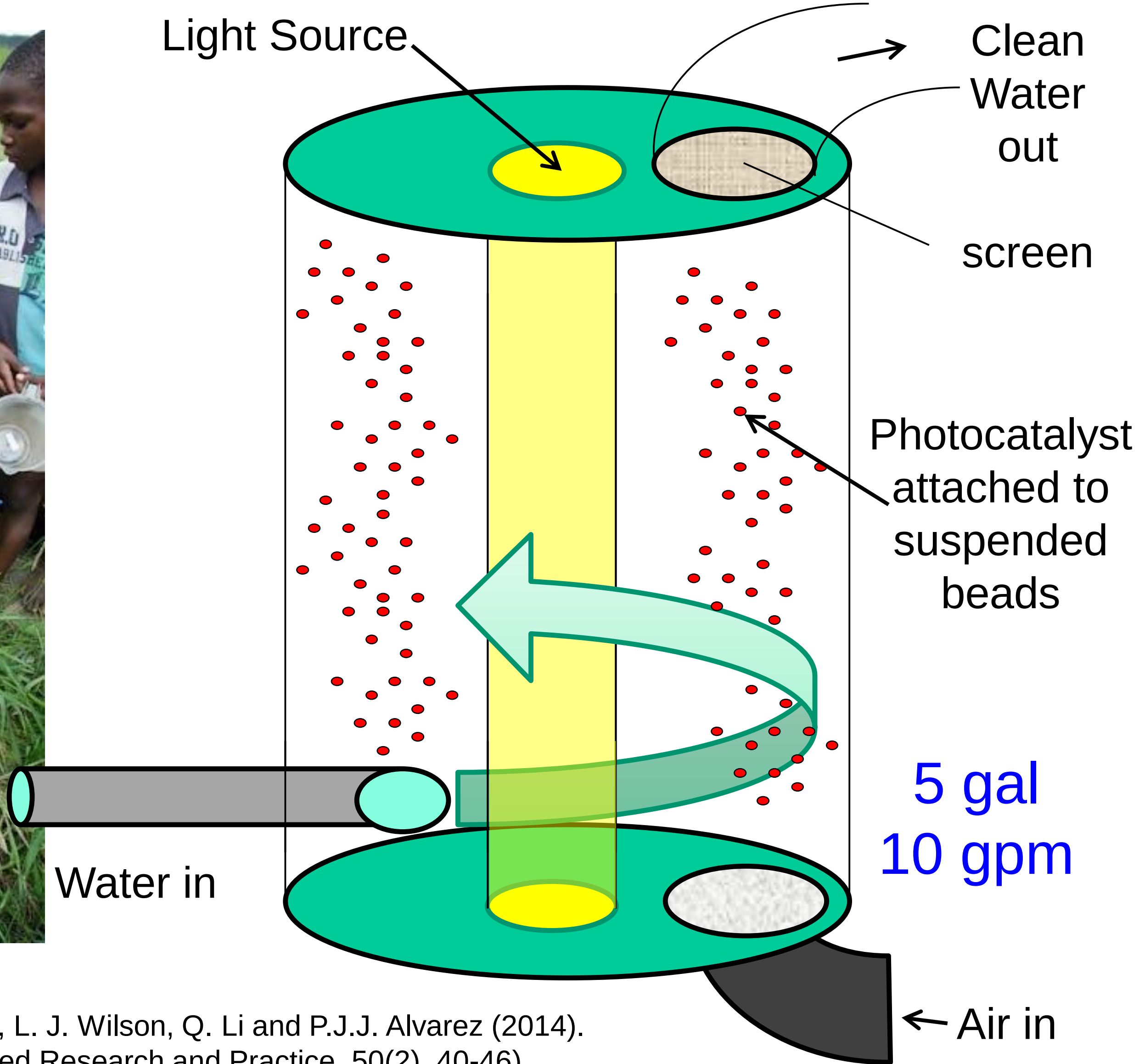






Fluidized Bed Photocatalytic Reactor for Point-of-Use Disinfection and Pesticide Removal

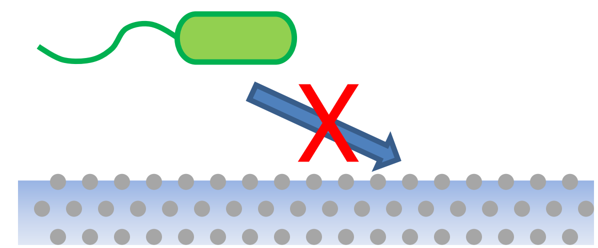




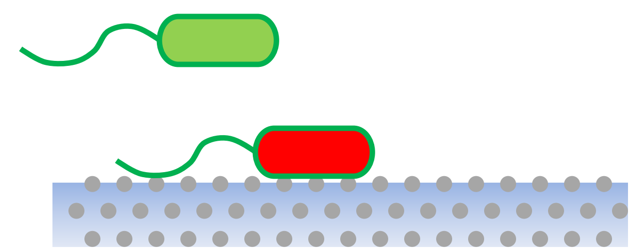
Brame J., V. Fattori, R. Clarke, Y. Mackeyev, L. J. Wilson, Q. Li and P.J.J. Alvarez (2014). Environmental Engineer and Scientist: Applied Research and Practice. 50(2), 40-46).

Biofouling Control

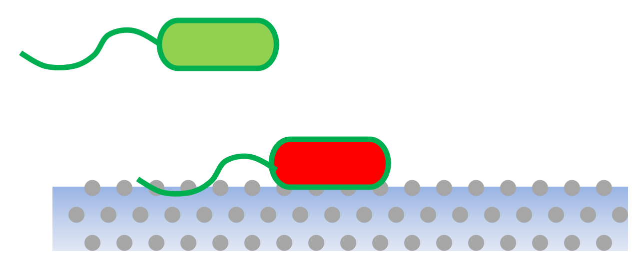
- *Discourage adhesion*
  - Nano-patterned topology
  - Surface chemistry
  - Interrupt quorum sensing



- *Release novel antimicrobials from porous nanocarriers*
  - Nanosilver or copper
  - D-amino acids

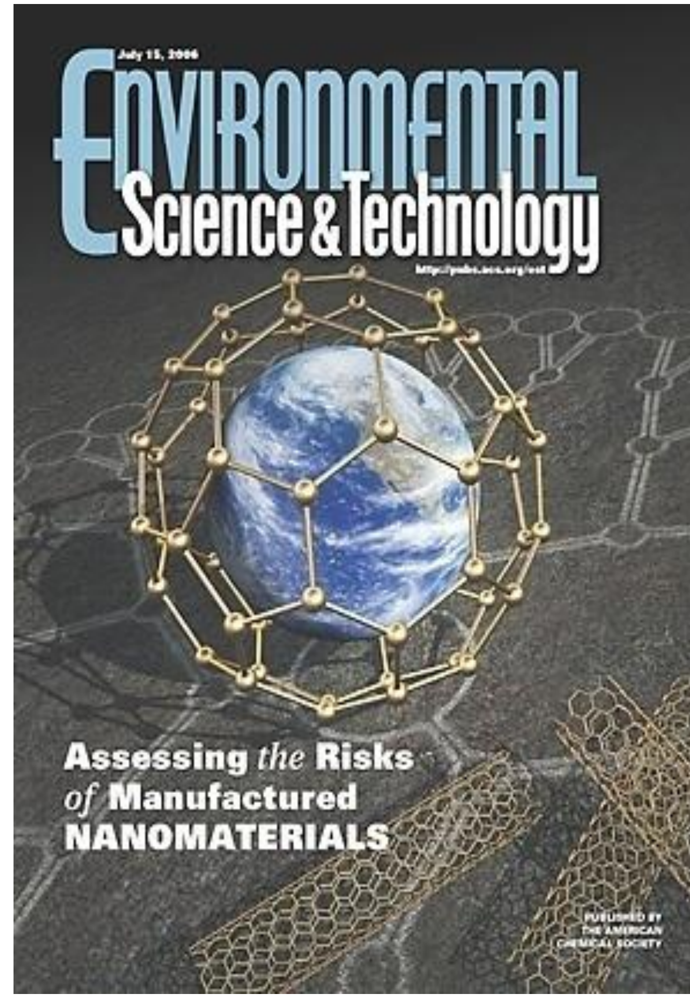


- *Photocatalytic ROS*
  - Semiconductors, e.g., TiO_2
  - Fullerene derivatives (self-cleaning surfaces)

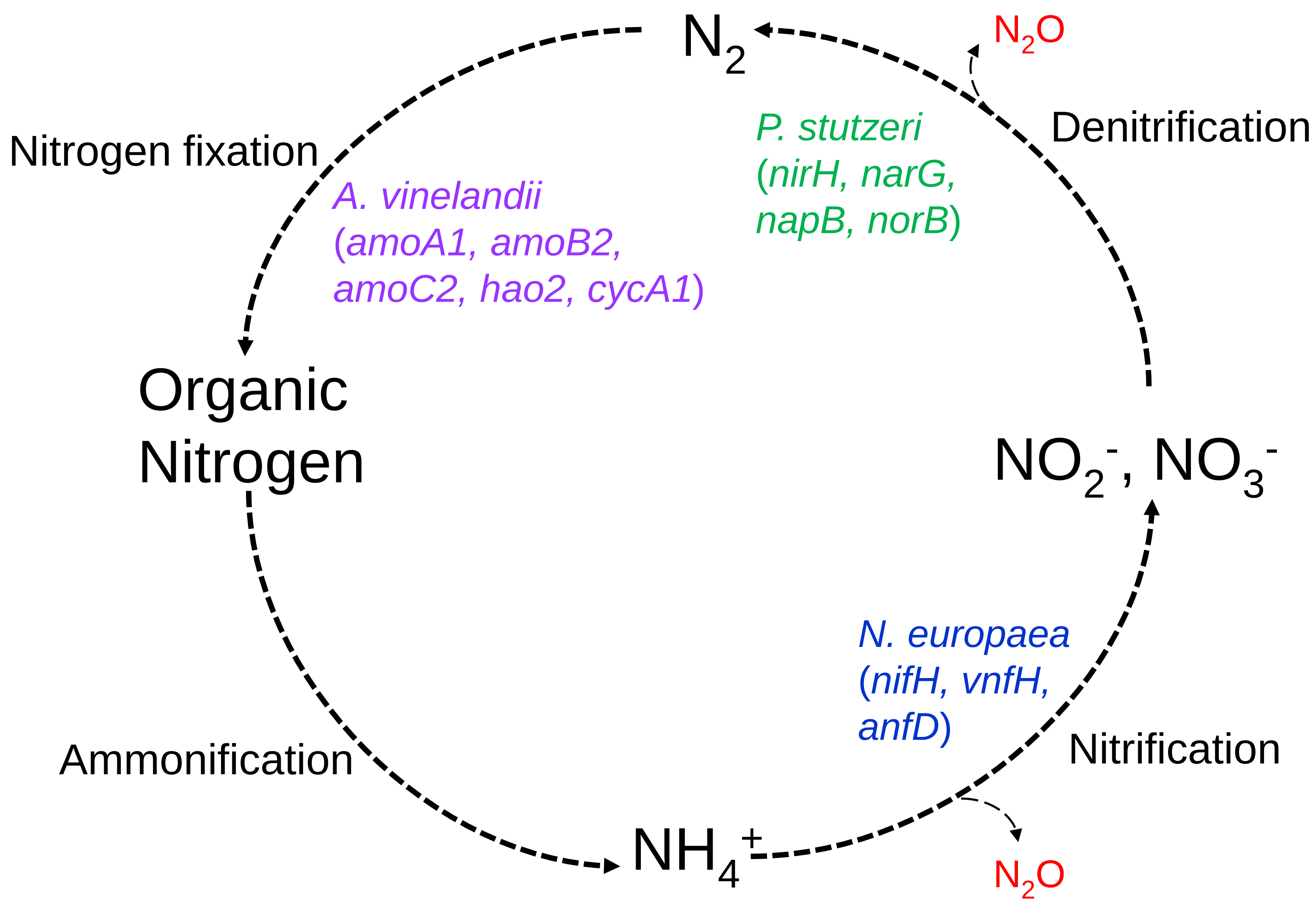


Conclusions

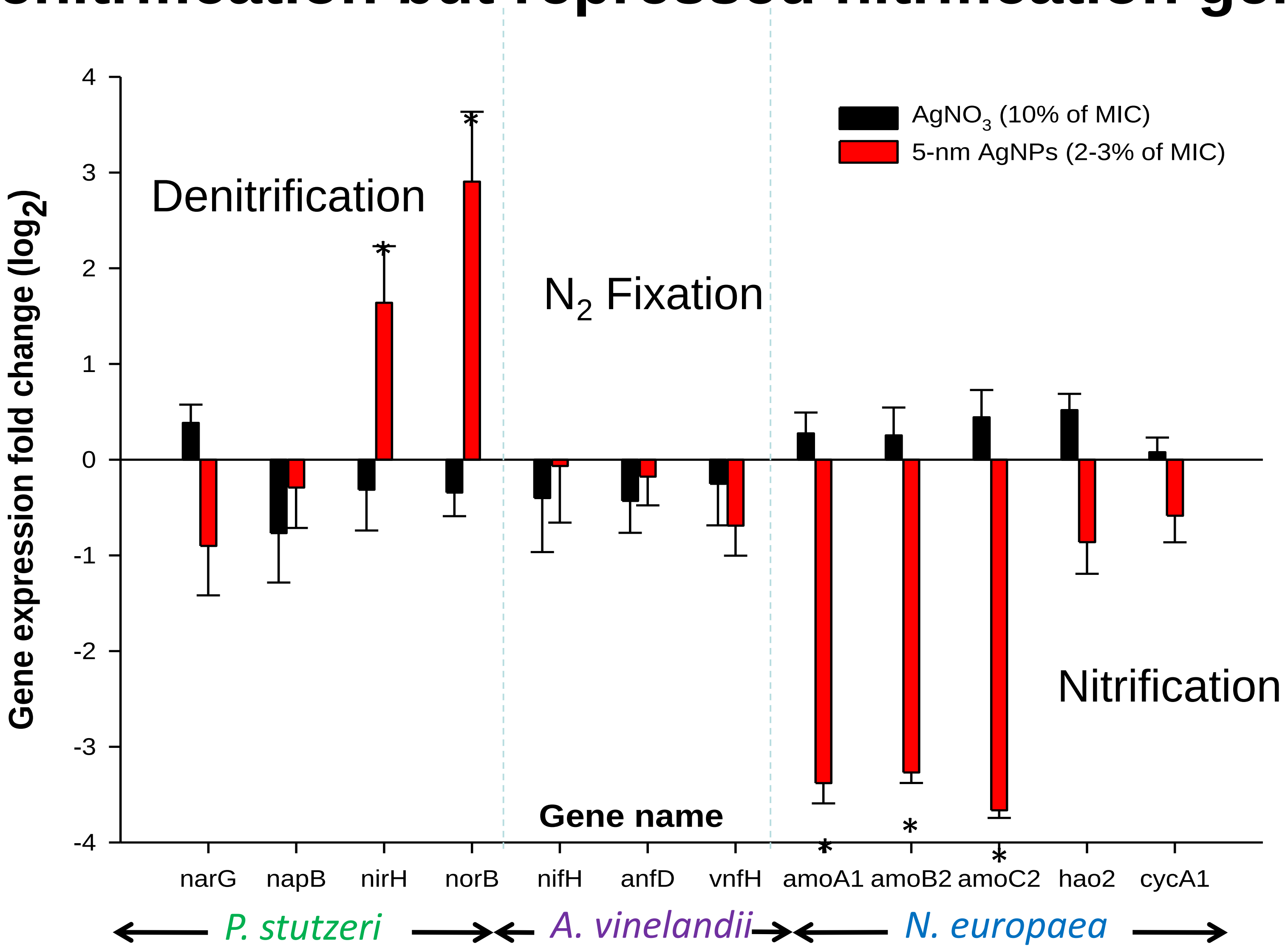
- Ecotoxicology
- Biodiversity and food webs?
- Biogeochemical cycling?
- *Mitigated by NOM, salts*



Potential Impacts to the N cycle:



Sub-lethal concentration of AgNPs induced denitrification but repressed nitrification genes

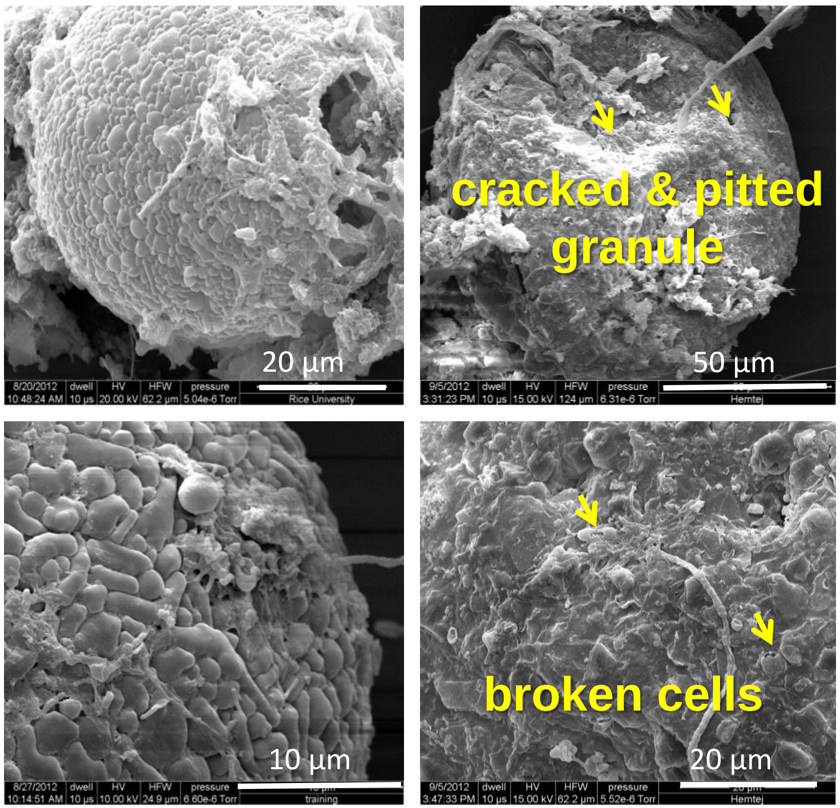


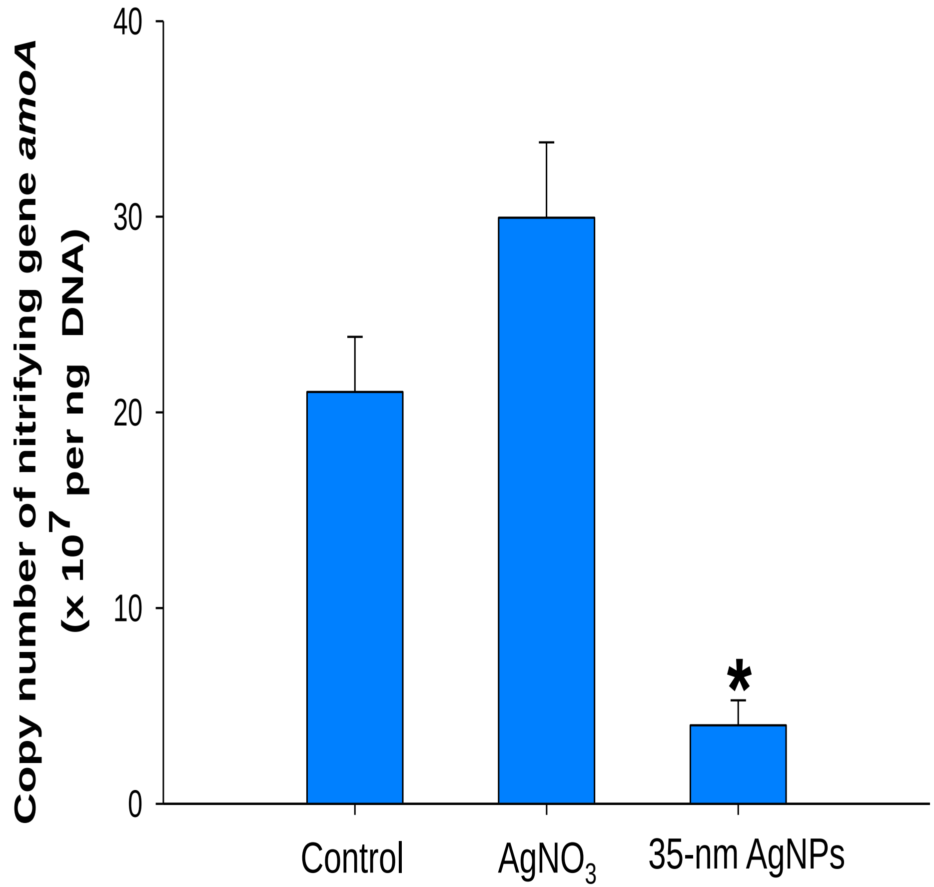
Yang Y., J. Wang, H. Zhu, V.L. Colvin and P.J.J. Alvarez (2013). Environ. Toxicol. Chem. 32 (7): 1488–1494

But AgNPs had higher impact than Ag^+ on activated sludge

Control

35-nm AgNPs (40 ppm)





AgNPs damaged AS floc, which can affect clarification and recycling

AgNPs decreased abundance of nitrifiers, hinders N removal

Yang Y., J. Quensen, J. Mathieu, Q. Wang, J. Wang, M. Li, J. Tiedje, and P. Alvarez (2014). Wat. Res. 48:317-325.

Synthetic Nanoparticles in Natural Water

Example

$1.5 \cdot 10^3$ manufactured nanoparticles/ml

10^8 natural nanoparticles/ml (erosion, eruptions, combustion, etc)

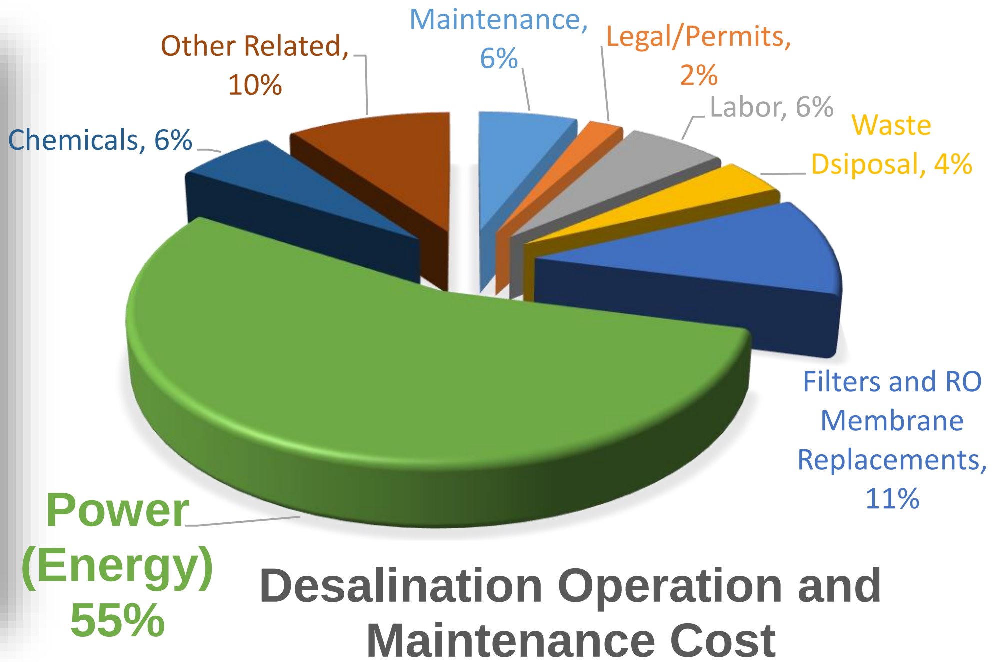
Water for Energy – A Trillion-Dollar Challenge

Tailor-treat & reuse produced waters for EOR, agriculture, desert greening, etc.

Water/Oil Ratio = 10 (US), 14 (Can.) **$1 trillion/yr challenge***

*http://www.twdb.state.tx.us/Desalination/TheFutureofDesalinationinTexas-Volume2/documents/B3.pdf

Energy for Water Treatment & Distribution

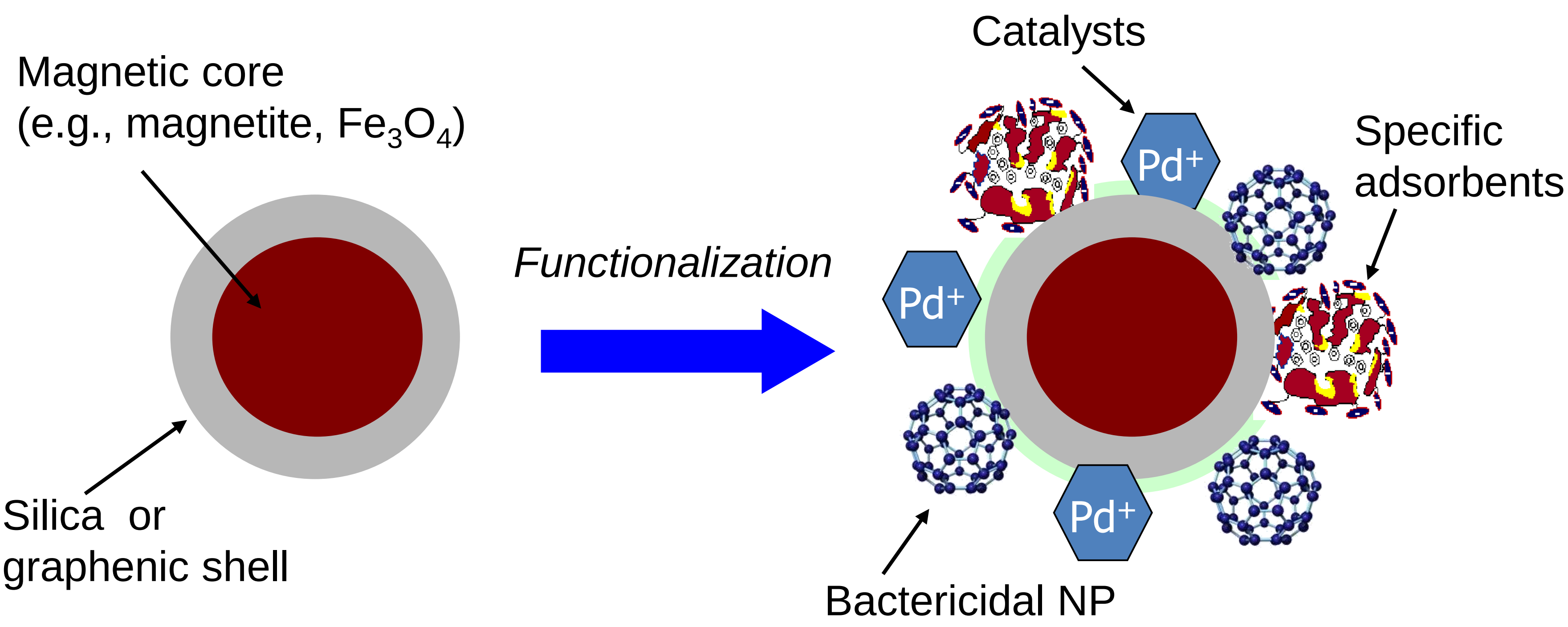


- 20% of electrical energy use in cities is for moving water[1]
- Desalination and wastewater reuse is very energy-intensive[2]

1. Electric Power Research Institute, Inc. Water & Sustainability (Volume 4): U.S. Electricity Consumption for Water Supply & Treatment –The Next Half Century. **2002**.
2. Water Reuse Association, Seawater desalination cost, January 2012

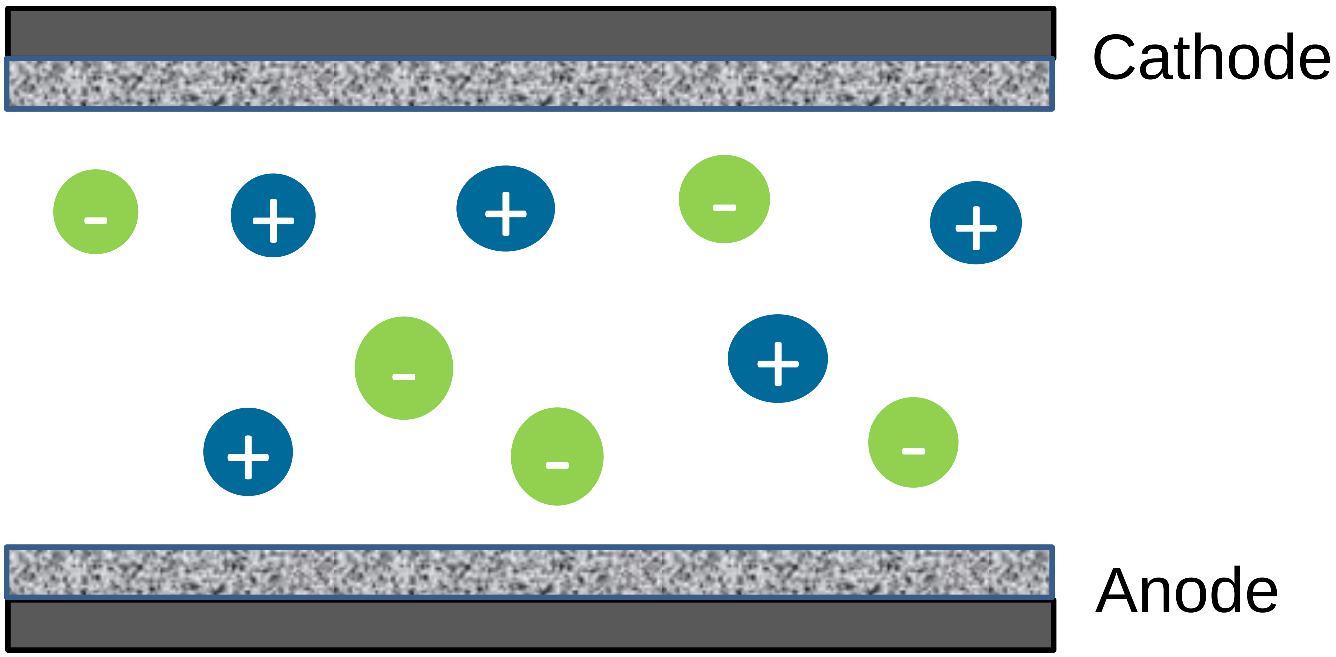
Multifunctional Nano-Sorbents

Selective removal of target contaminants by functionalized nanoparticles supported in macroscale structures or subject to (low-energy) magnetic separation for enhanced removal kinetics & reuse



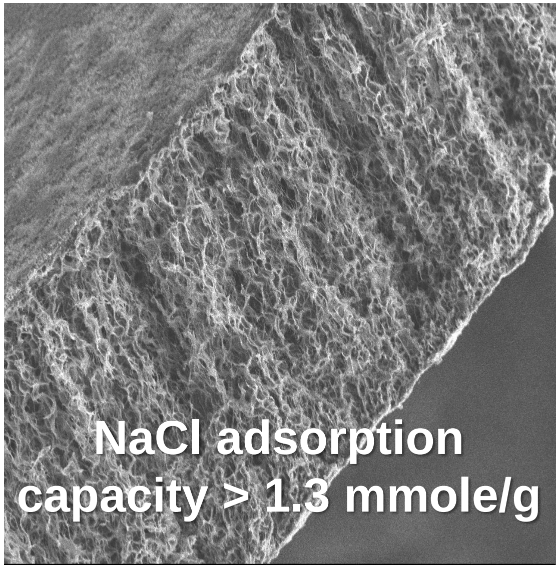
Electrosorption for Scaling Control

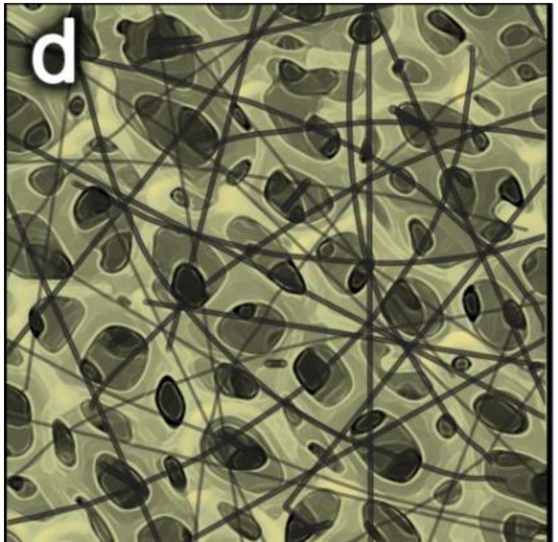
Nanocomposite electrodes to remove multivalent ions from brines, and generate smaller waste streams

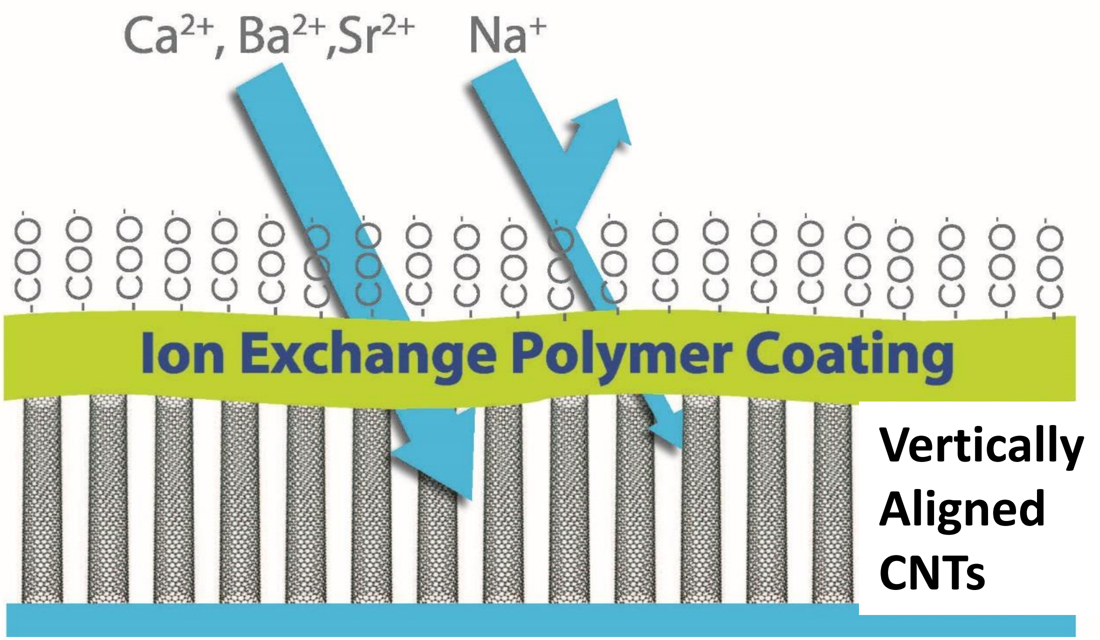


Nano-Enabled CDI

IX polymers enable preferential removal of divalent cations that cause scaling

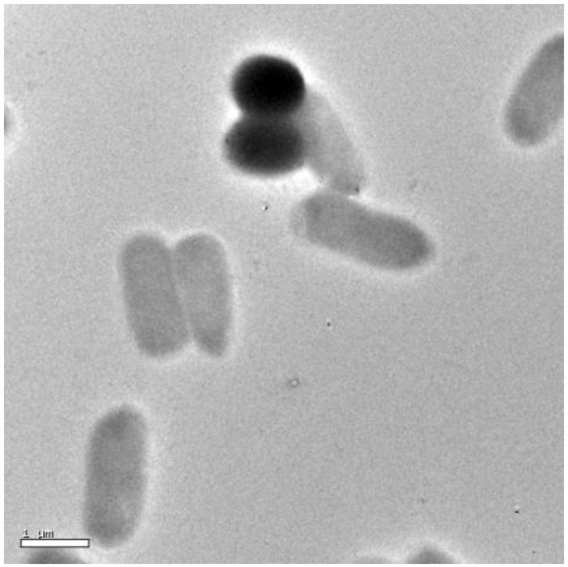




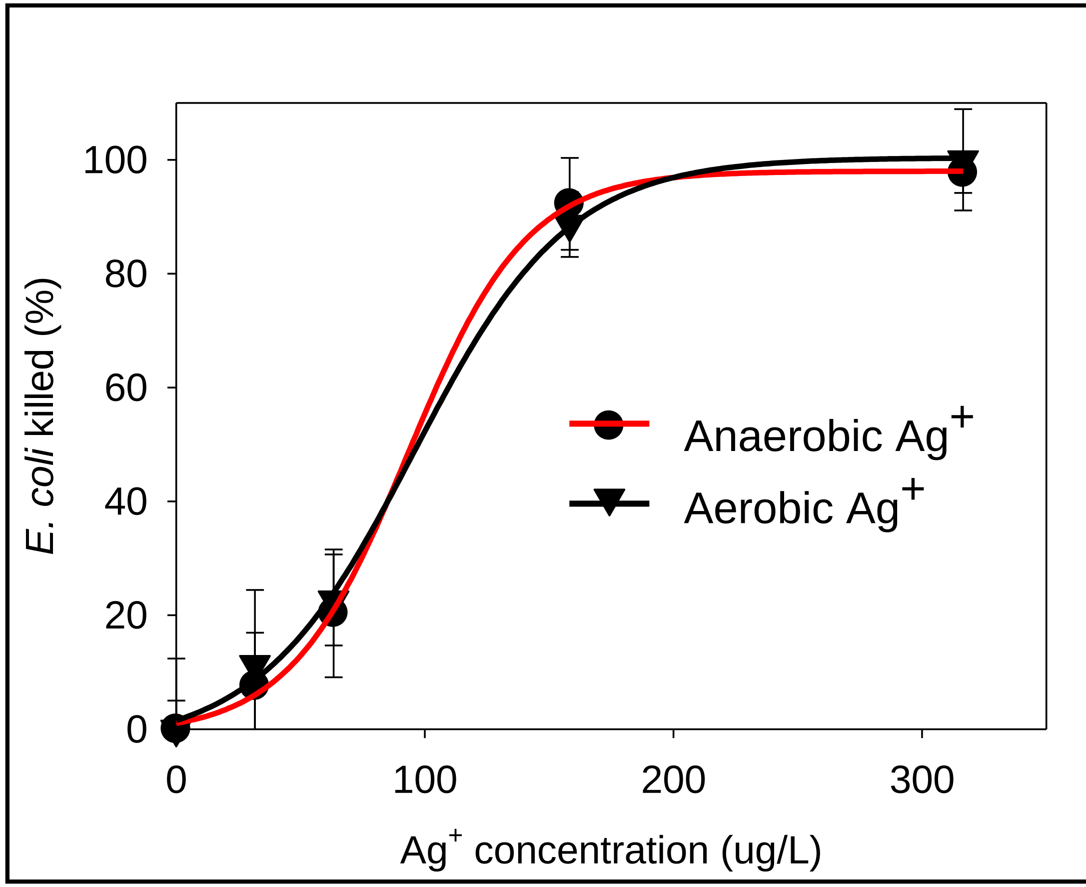


CNTs/graphene enhance sorption capacity, kinetics, mechanical strength and electrical conductivity

Similar Ag^+ Toxicity under Aerobic & Anaerobic Conditions



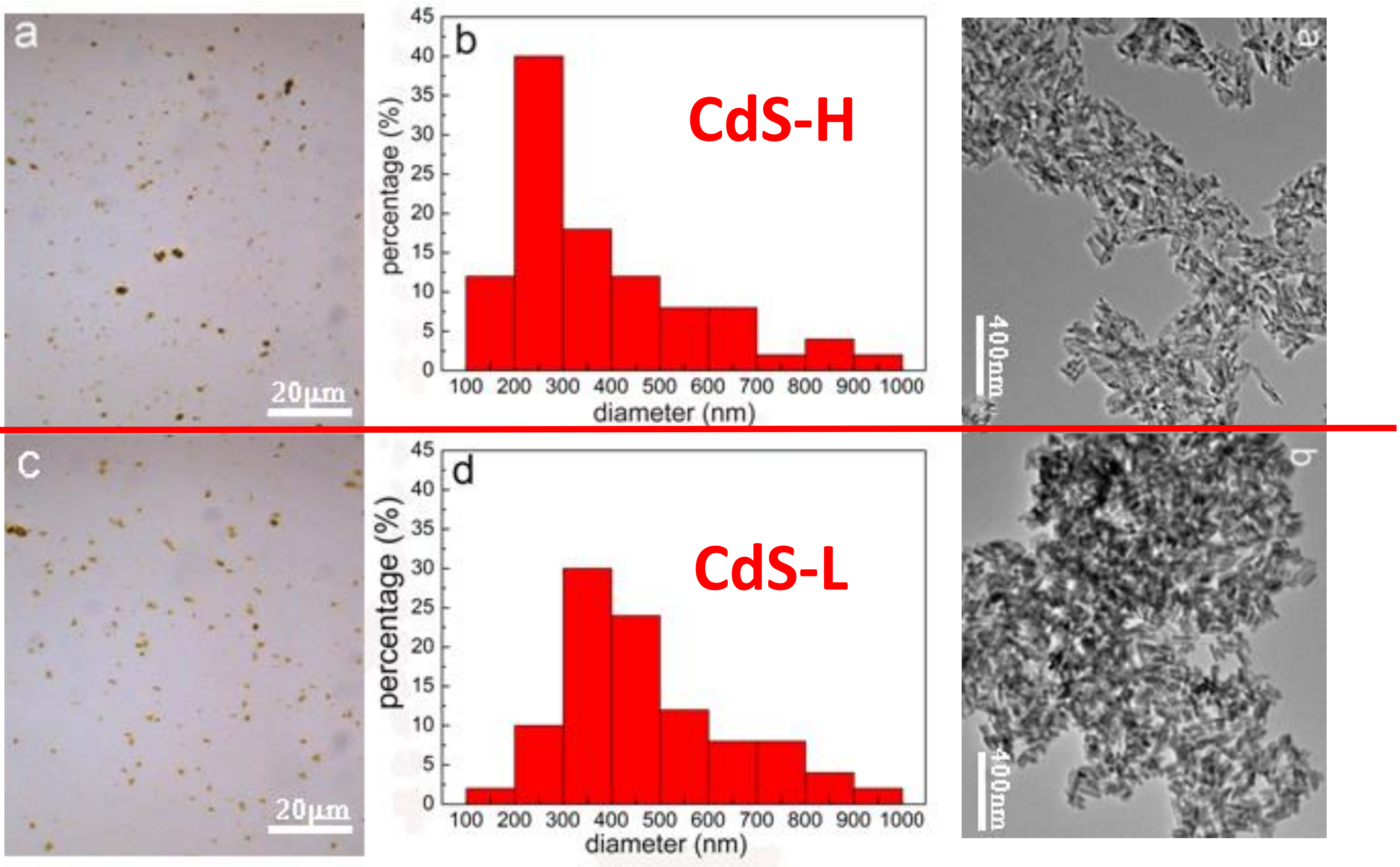
E. coli **is facultative**



Statistically undistinguishable difference

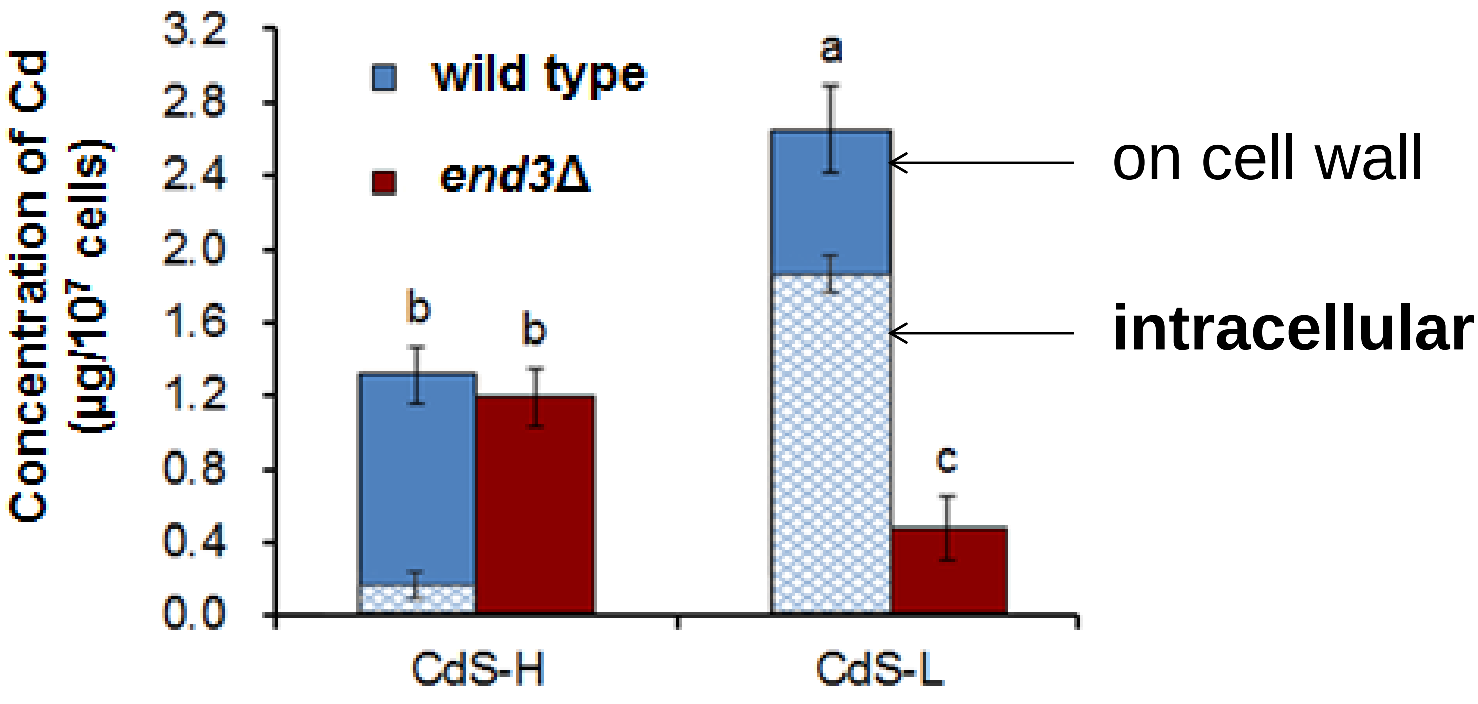
Xiu Z., J. Ma and PJJ. Alvarez, *Environ. Sci. Technol.*, **2011**

Similar morphology and aggregate size



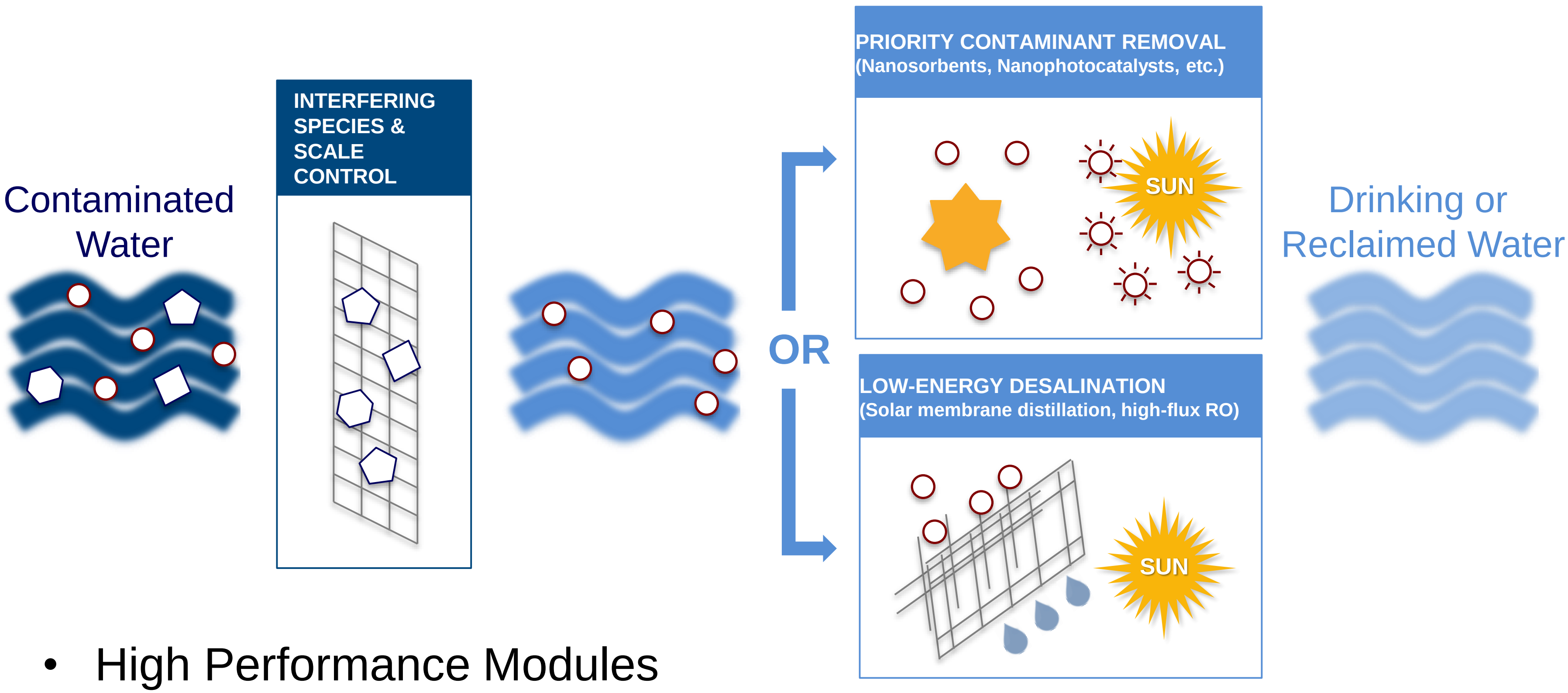
Total Cd accumulation in wild-type versus endocytosis-deficient (*end3Δ*) mutant yeast

- No difference for CdS-H (mostly trapped in wall)
- Significantly higher Cd accumulation for CdS-L in wild-type due to endocytosis



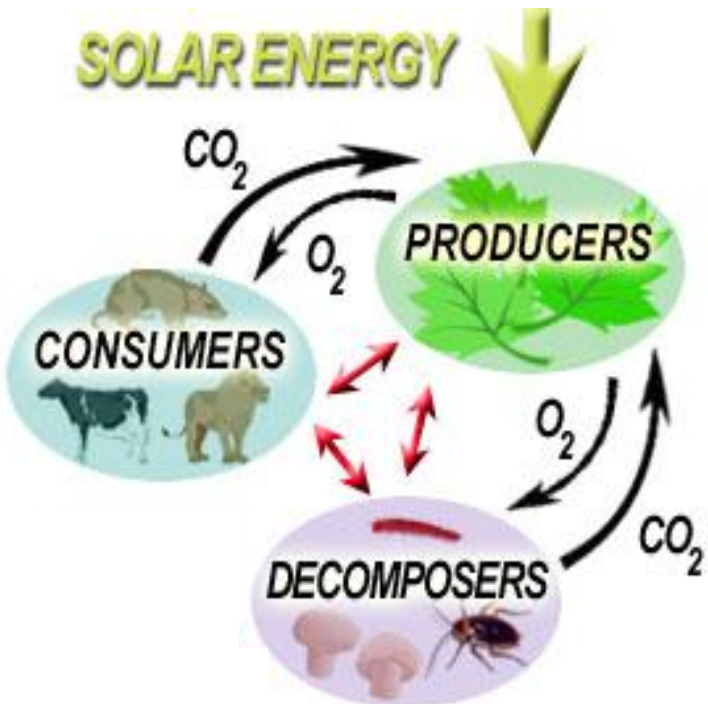
Modular Treatment Systems

Match treated water quality to intended use



- High Performance Modules
- Lower Chemical Consumption
- Lower Electrical Energy Requirements
- Less Waste Residuals
- Flexible and Adaptive to Varying Source Waters

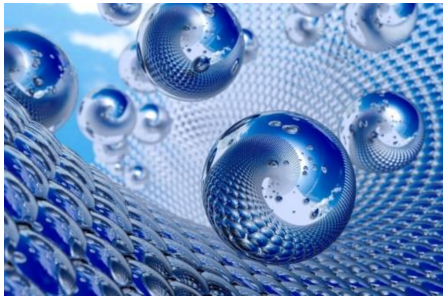
Microbial-nanoparticle Interactions to Inform Risk Assessment



- Bacteria are at the foundation of all ecosystems, and carry out many ecosystem services
- Disposal/discharge can disrupt primary productivity, nutrient cycles, biodegradation, agriculture, etc.
- Antibacterial activity may be fast-screening indicator of toxicity to higher level organisms (*microbial sentinels*?)

NEWT Center

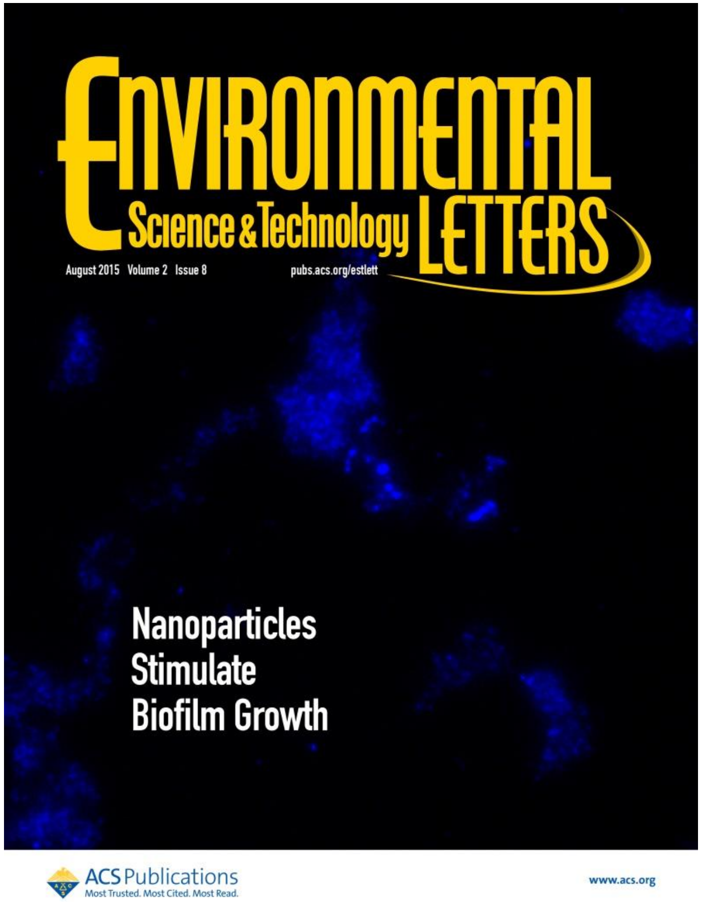
- The Nanotechnology-Enabled Water Treatment Center is the first national center to develop next-generation water treatment systems enabled by nanotechnology.

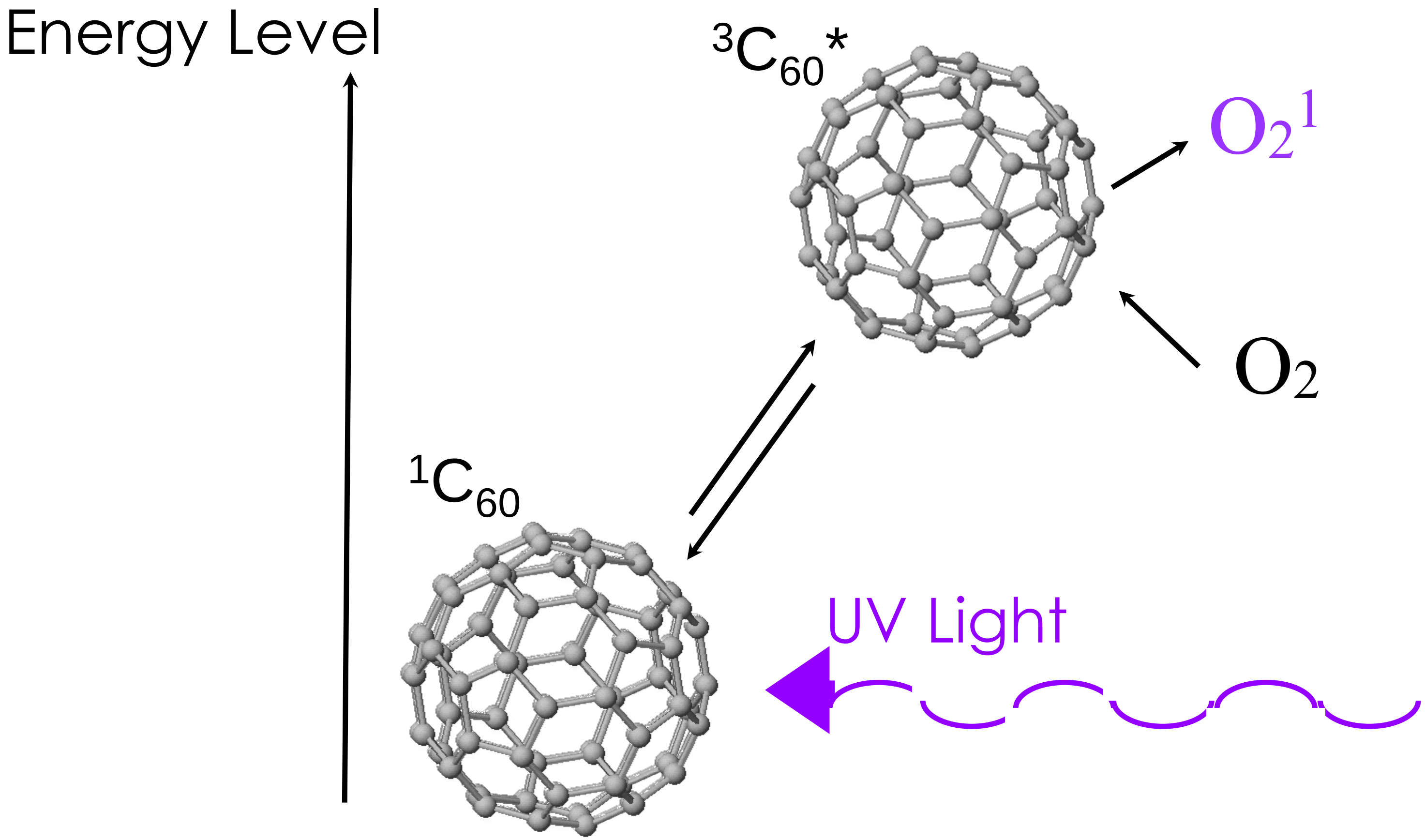


- ERC from NSF ($37M for 10 yr)
- Innovation ecosystems with numerous industrial partners that help shape research.

Summary of nAg Release Implications

- Development of bacterial resistance & biofilm formation?
- Impacts to biological wastewater treatment processes?
- Impact nitrogen cycling?

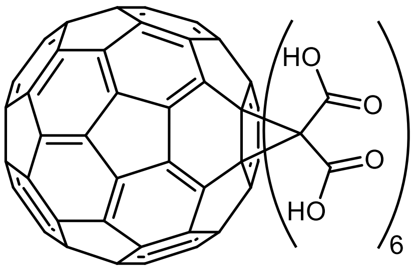




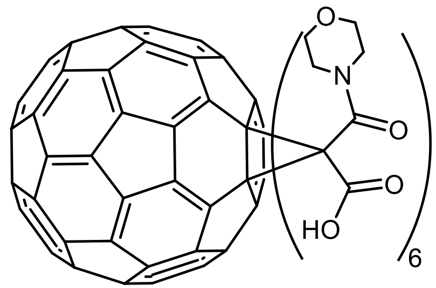
Light excites C_{60} to triplet state. Energy transfer between $^3C_{60}^*$ and molecular oxygen gives rise to singlet oxygen ($^1O_2$)

Hotze M., J. Labille, P.J.J. Alvarez and M. Wiesner (2008). Environ. Sci. Technol. 42, 4175–4180

“Water Soluble” Derivatized Fullerenes

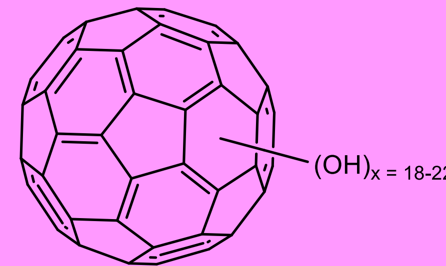


HC1



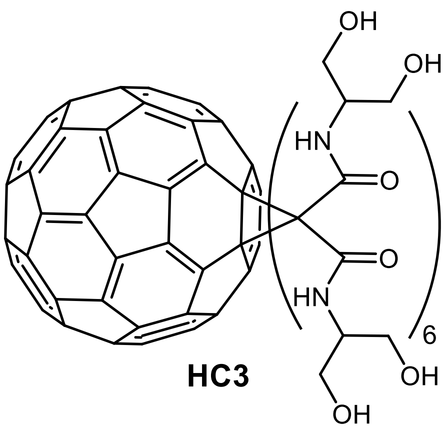
HC2

vs

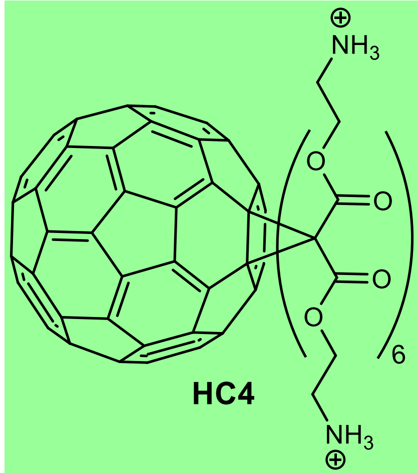


Fullerol

* Commercially Available, MER Corp.



HC3



HC4

* Synthesized in Lon Wilson’s lab, Dept of Chemistry, Rice University (Bingel reaction)

Superior $^1O_2$ Production confirmed by EPR & Laser Flash Photolysis