Nanotechnology-Enabled Water Treatment:

A Vision to Enable Decentralized Water Treatment and Reuse

Pedro J.J. Alvarez

NSF

RICE ASU UTEP Yale

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)

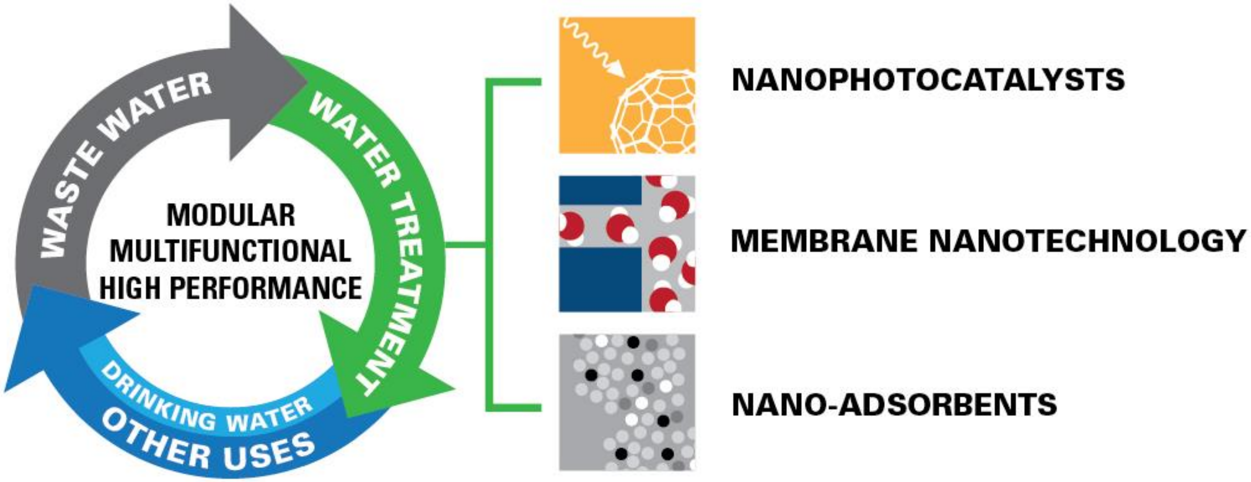
http://switchboard.nrdc.org/blogs/rhammer/fracking-2.jpg

Why Nano?

Leap-frogging opportunities to:

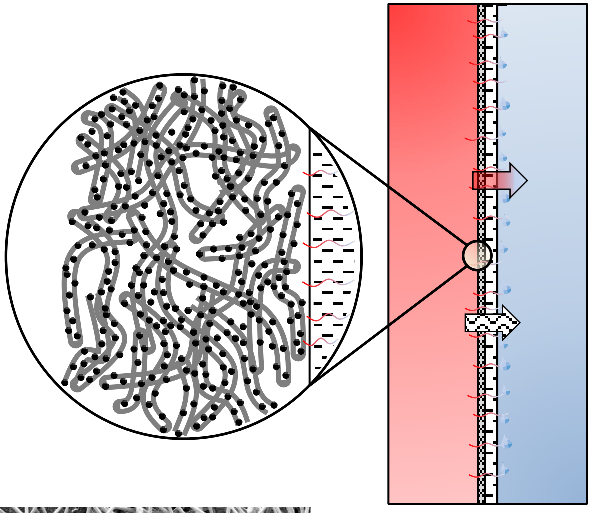
- Develop high-performance multifunctional systems that are easy to deploy, can tap unconventional water sources, match treated water quality to intended use & reduce treatment cost.

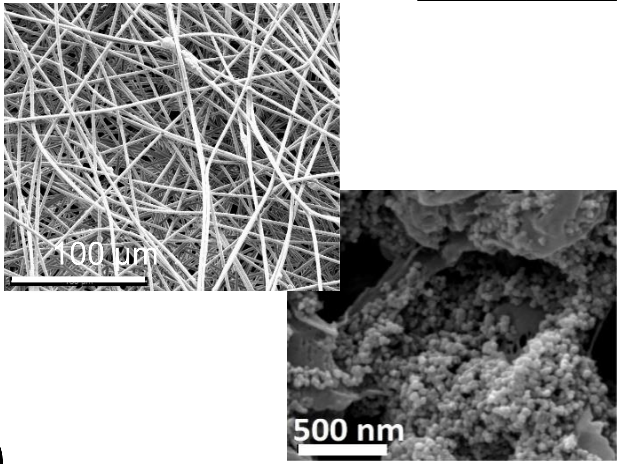
- Transform predominantly chemical treatment processes into modular and more efficient catalytic and physical processes that exploit the solar spectrum and generate less waste.



High- Level Research Questions

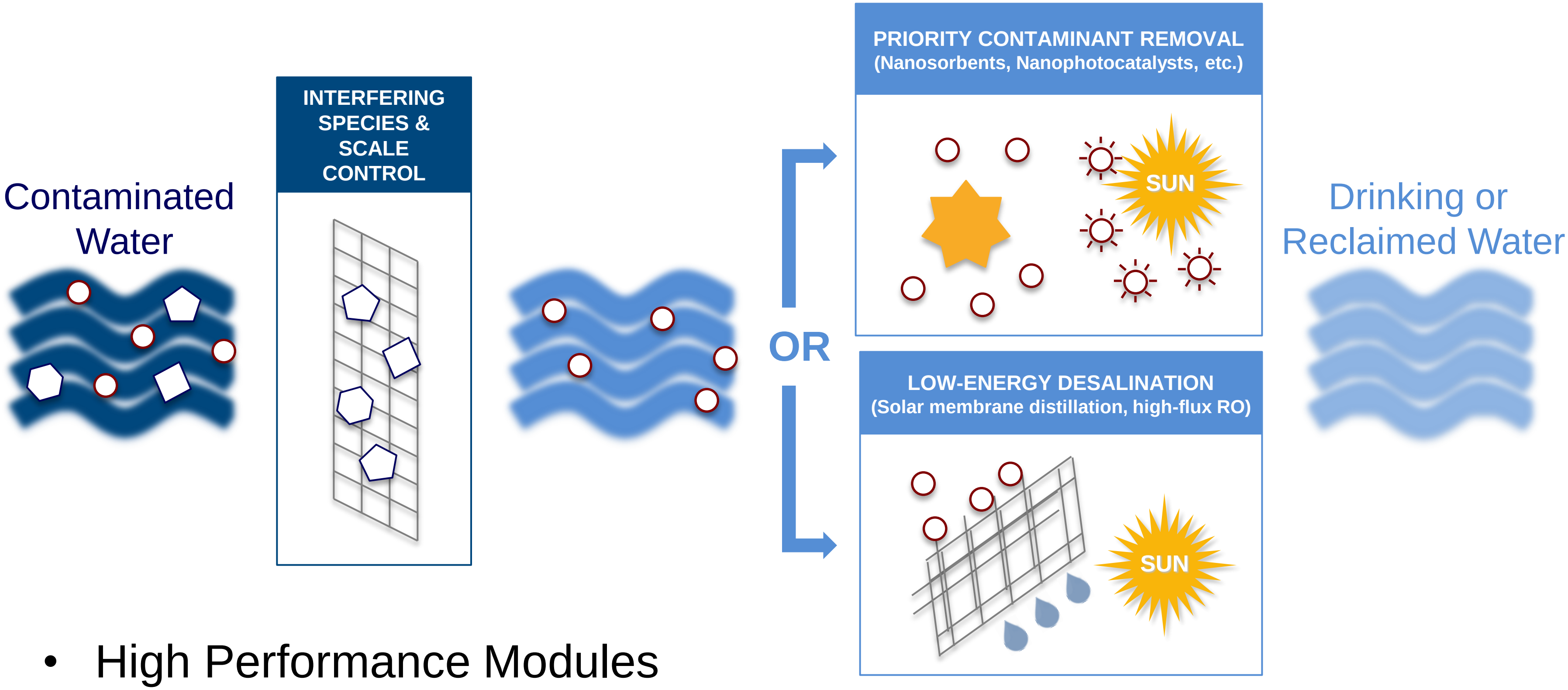
- How should we use novel nano-scale properties for water purification?
- How can nanomaterials be attached to surfaces or embedded into scaffolding without losing their functionality?
- How can we harness solar energy directly to reduce costs of water purification?
- What safety concerns must be addressed to commercialize nano-enabled water technologies? (Use bening ENMs & immobilize them)





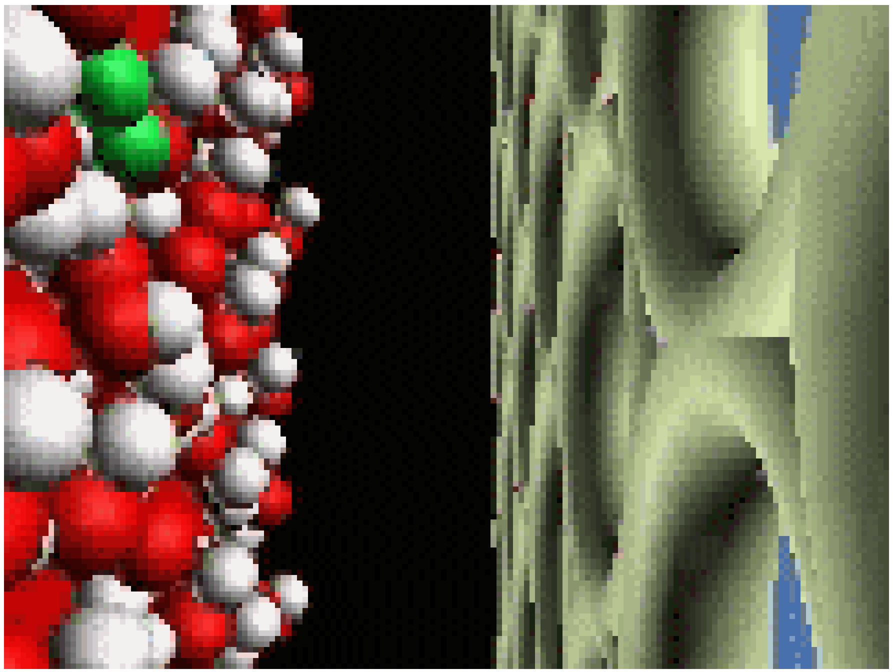
Modular Treatment Systems

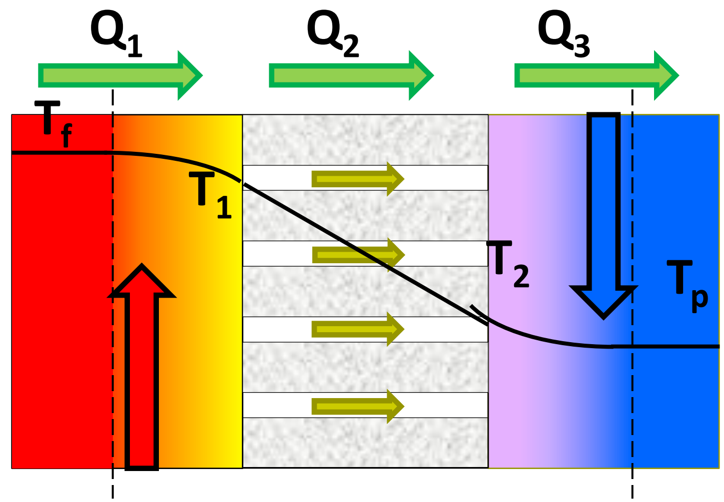
Match treated water quality to intended use



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

Example: Enhancing Membrane Distillation



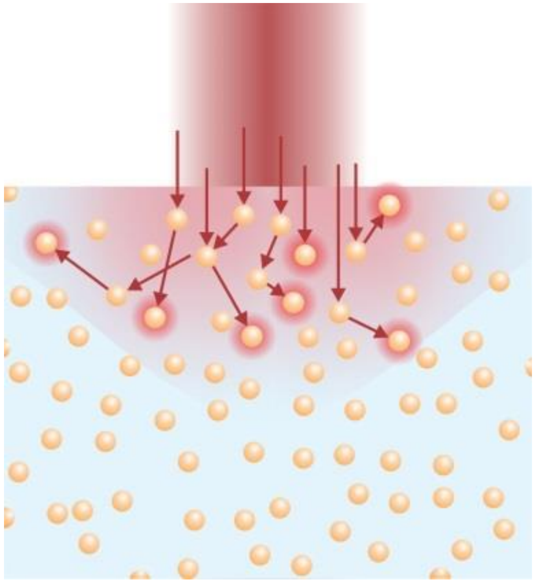


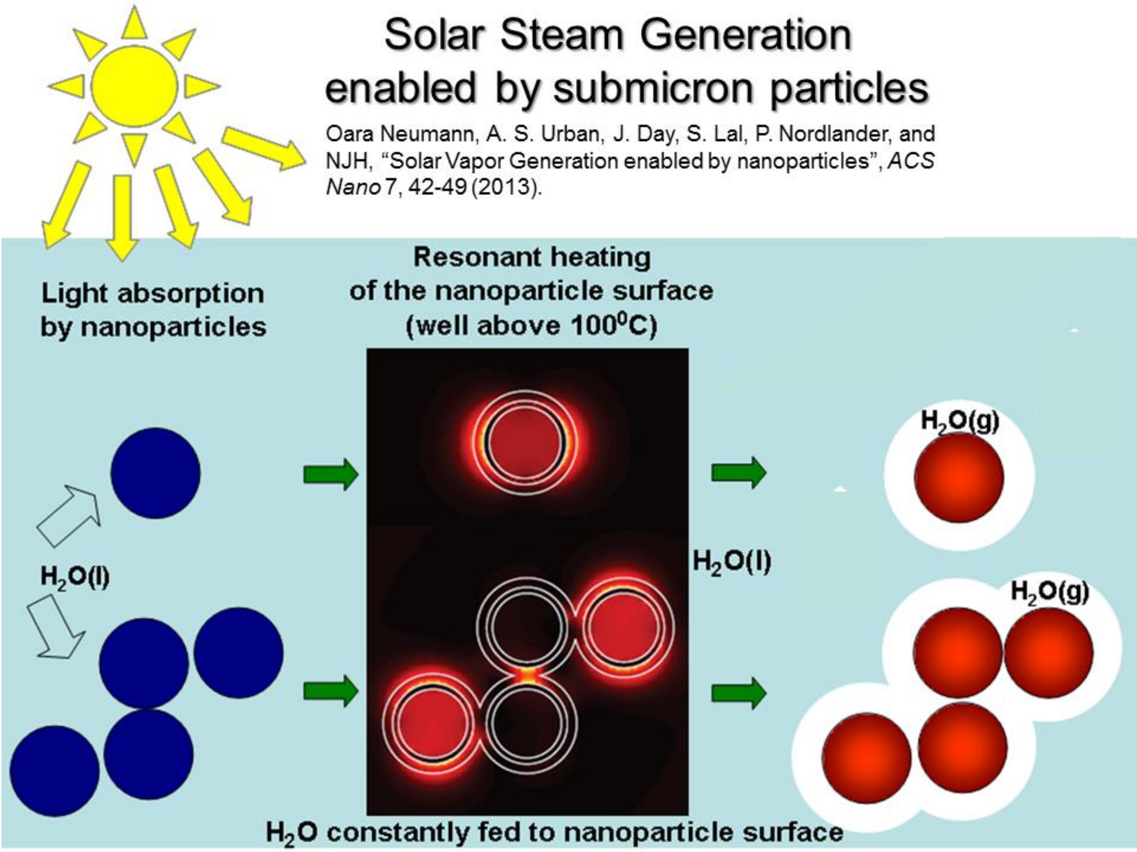
Temperature polarization:

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

Can reduce transmembrane temperature gradient by up to 70%

Photonics of Nanoparticles for Solar-Thermal Applications



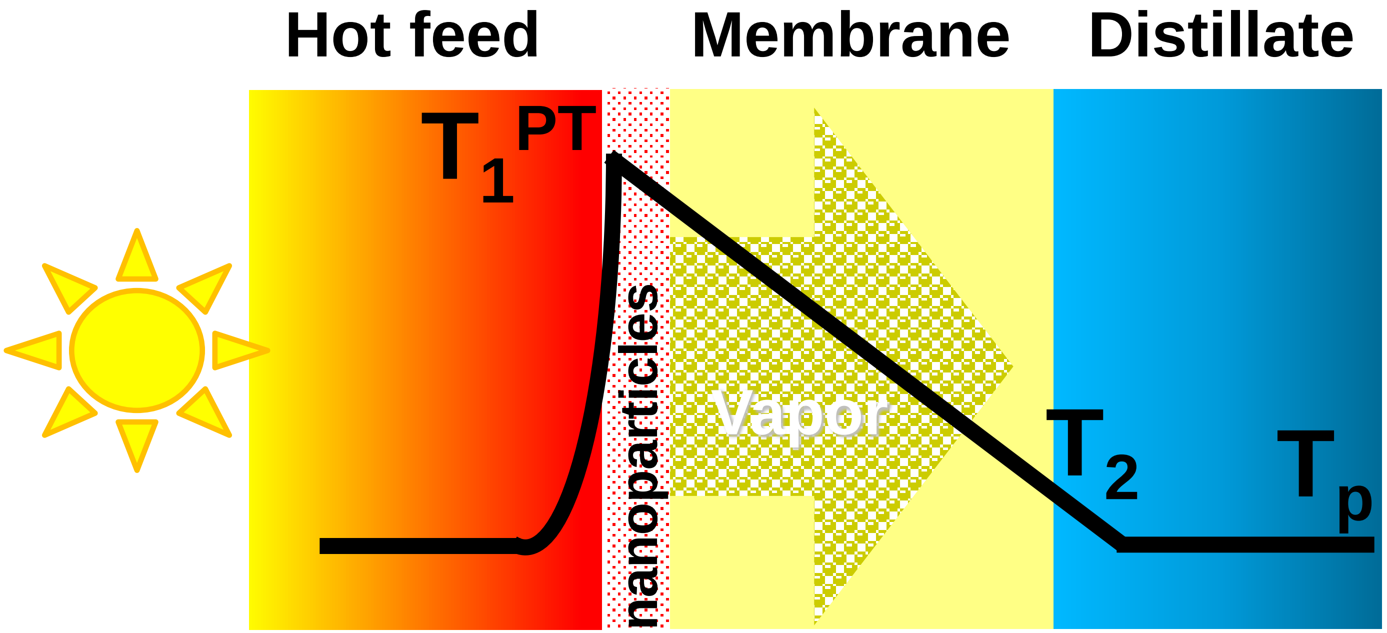


Light localization by multiple scattering confines solar energy, enabling high efficiency heat transfer

(Hogan, Urban, Ayala, Pimpinelli, **Nordlander & Halas**, N*anoLett.* **2014**, *14*, 4640-4645)

Enabling Technology

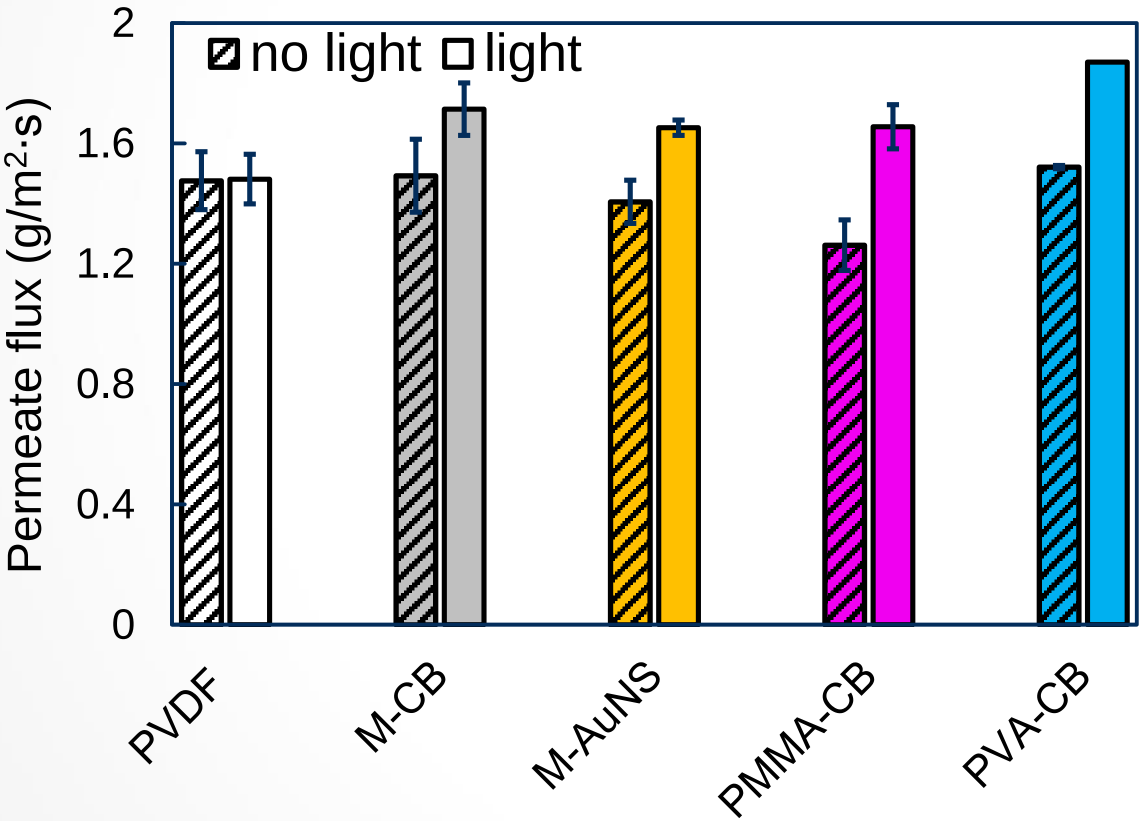
Direct solar membrane distillation for low-energy desalination

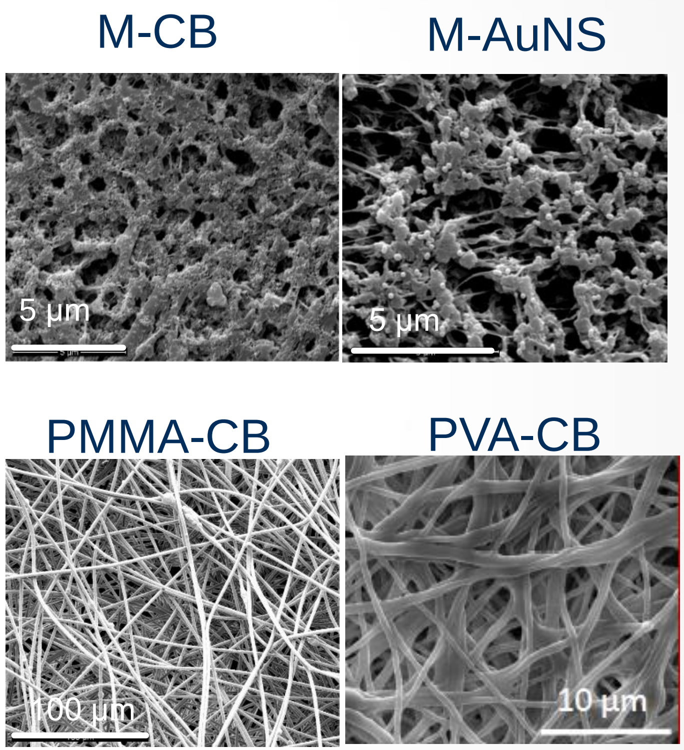


Higher ΔT→ increased efficiency!

Multifunctional membranes: Fouling-resistant, High-flux Self-cleaning

Photothermal Coating Enhances Membrane Permeate Flux

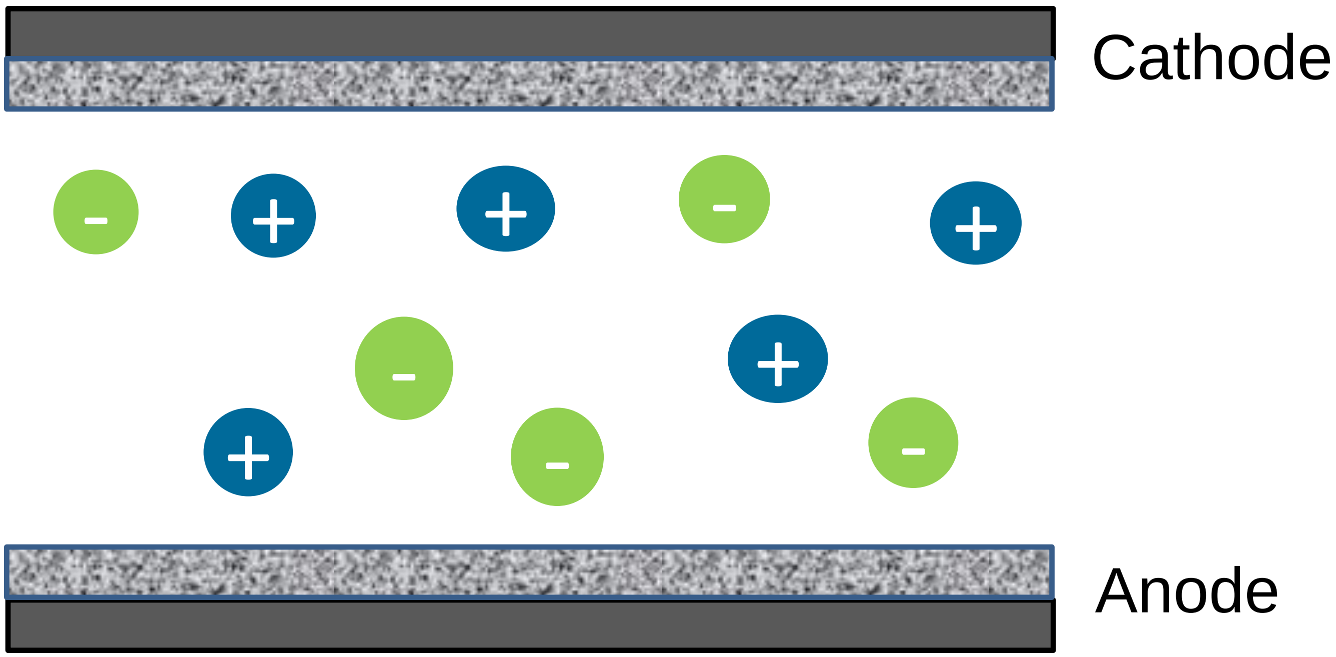




Tf = 35 °C, Tp = 20 °C
Light source: simulated sunlight at 1 sun unit

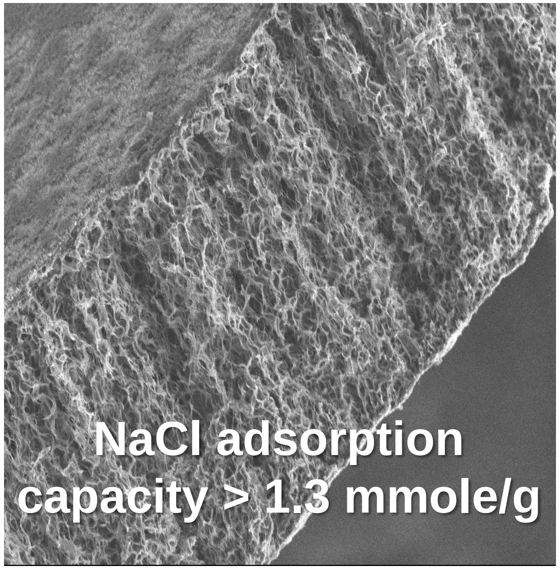
Enabling Technology
Electrosorption for Scaling Control

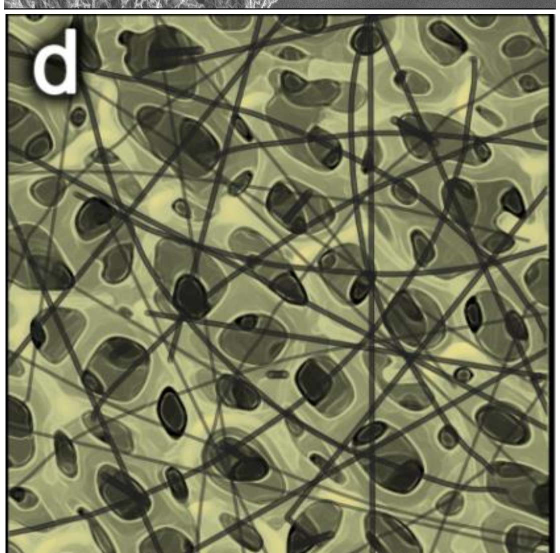
Nanocomposite electrodes to remove multivalent ions from brines, and generate smaller waste streams

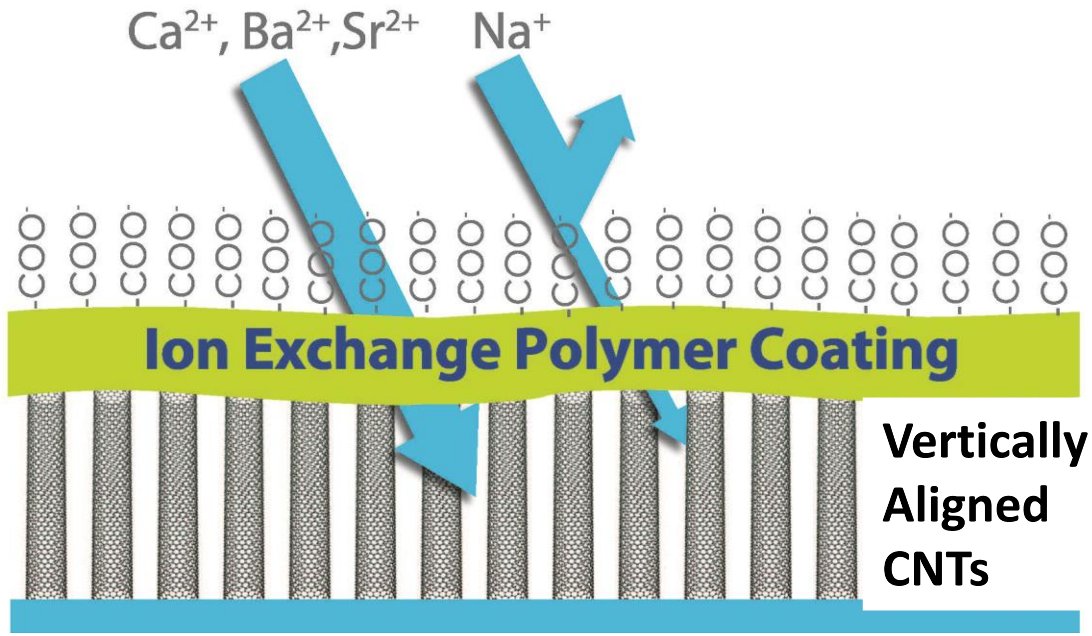


Nano-Enabled CDI for Scaling Control

IX polymers enable preferential removal of divalent cations that cause scaling



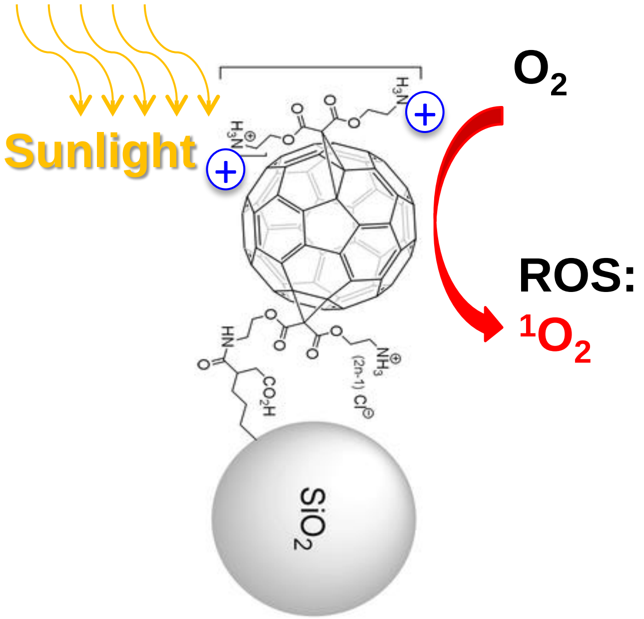




CNTs/graphene enhance sorption capacity, kinetics, mechanical strength and electrical conductivity.

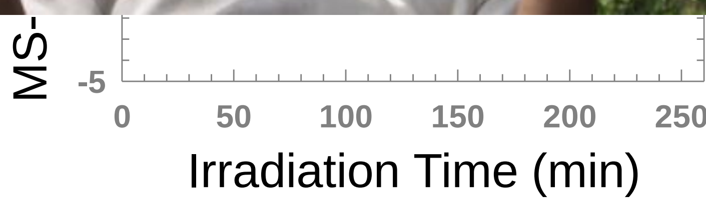
Enabling Technology
(Photo)Disinfection & Advanced Oxidation

Nano(photo)catalysts that use solar radiation to generate ROS that preferentially destroy resistant microbes and recalcitrant pollutants without generating harmful disinfection byproducts

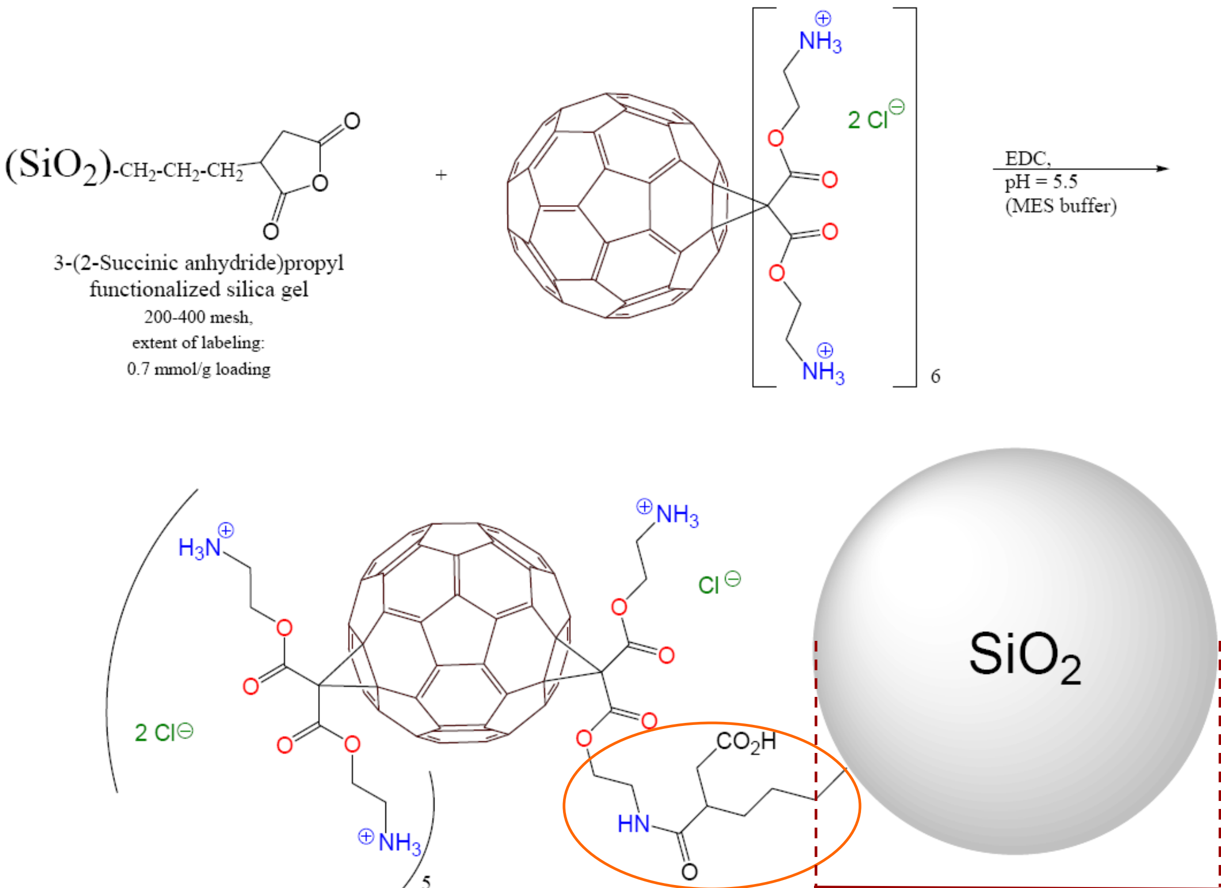


Immobilized Photocatalyst

Advantages of Amino-C_{60} as Photocatalytic Disinfectant



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

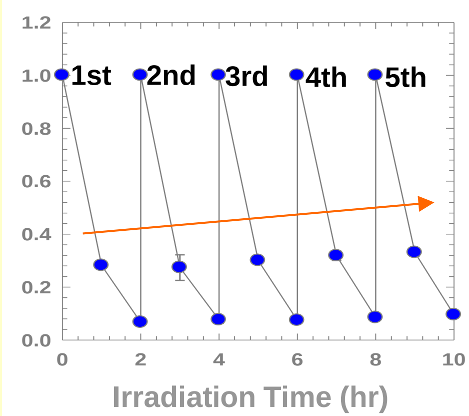


0.2 - 0.3 mm

EASILY SEPARABLE

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

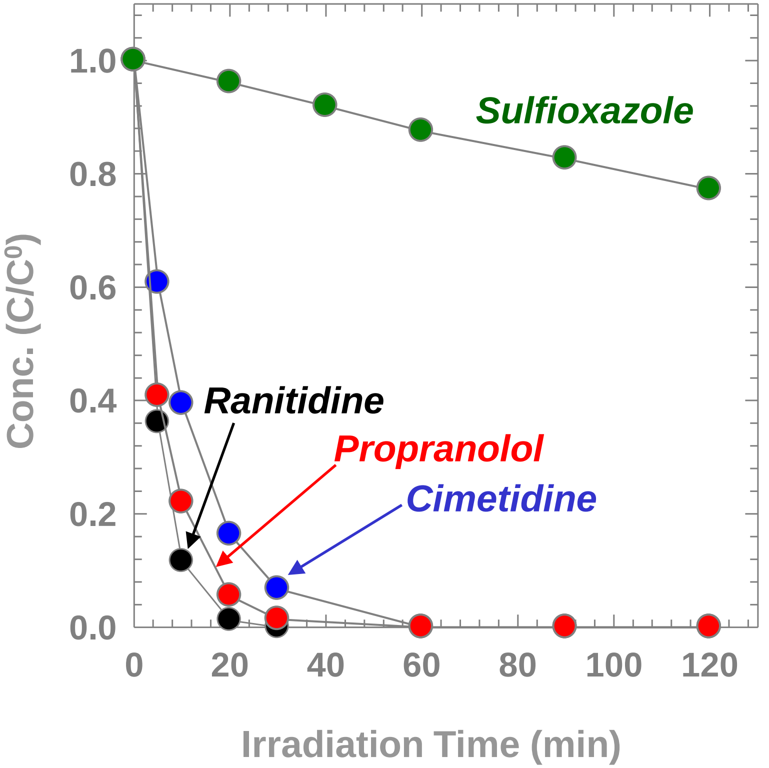
REPETITION TEST



No loss of photo-activity

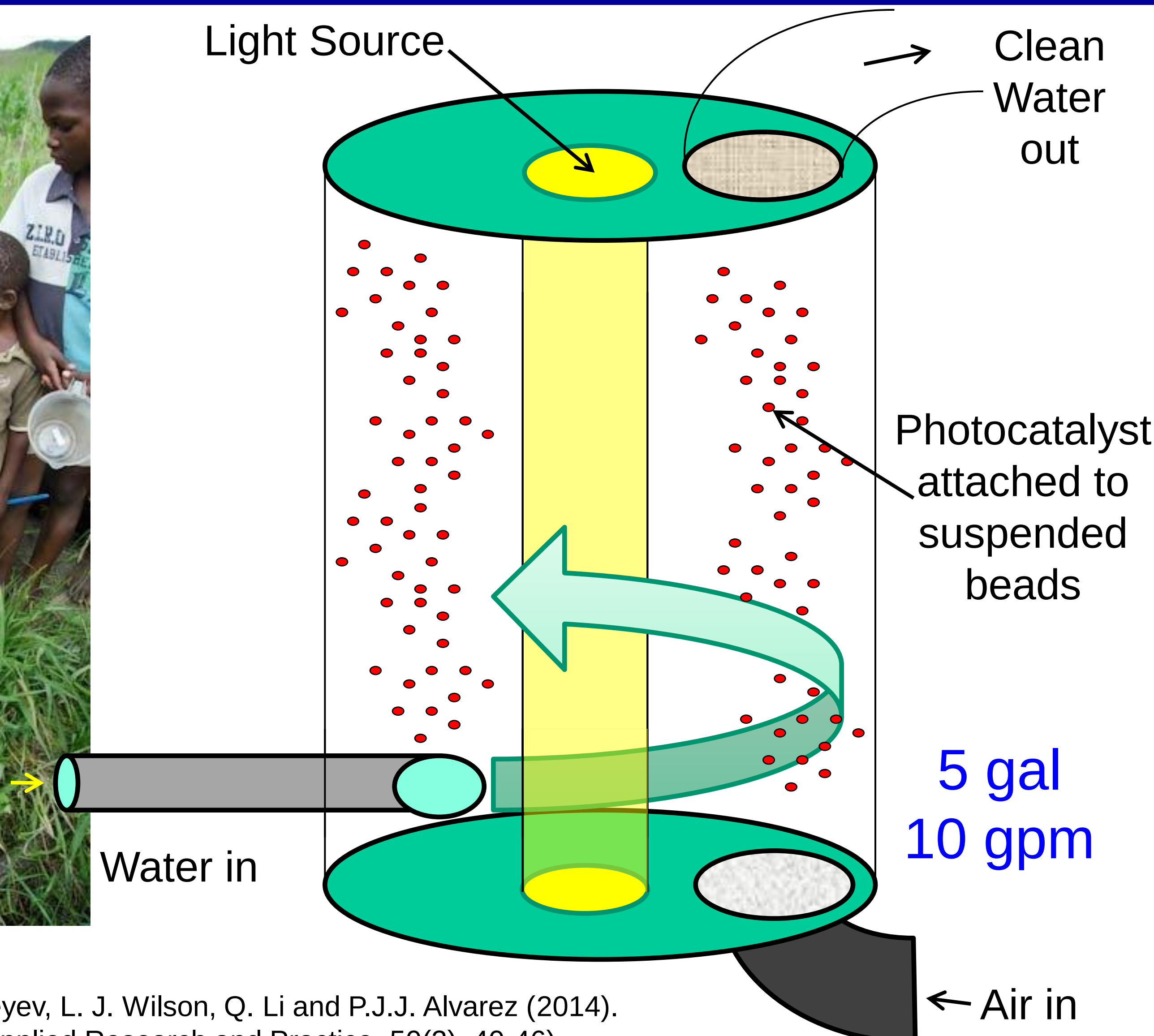
Lee, Mackeyev, Cho, Wilson, Kim and Alvarez (2010). *Environ. Sci. Technol.* 44: 9488–9495.

Photocatalytic treatment of emerging contaminants (pharmaceuticals, endocrine disruptors)



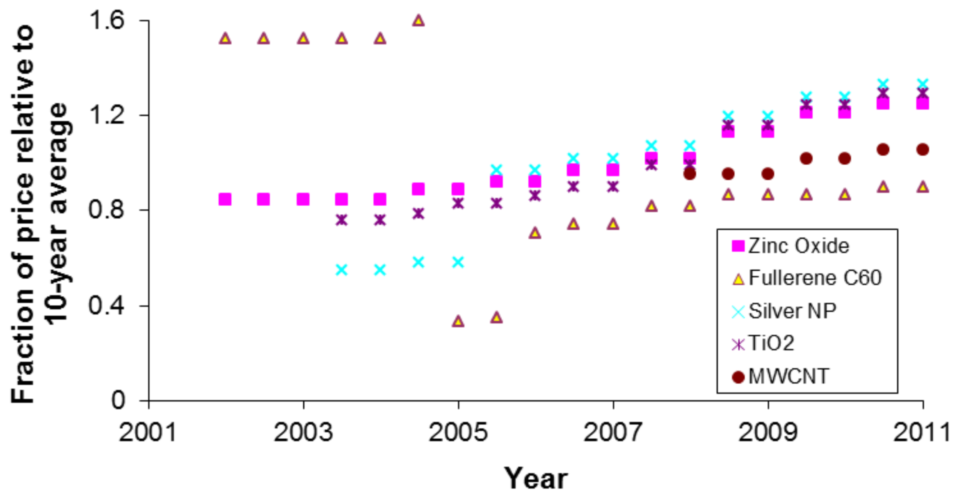
Lee J., S. Hong, Y. Mackeyev, C. Lee, L.J. Wilson, J-H Kim and P.J.J. Alvarez (2011). Environ. Sci. Technol. *45*: 10598–10604.

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

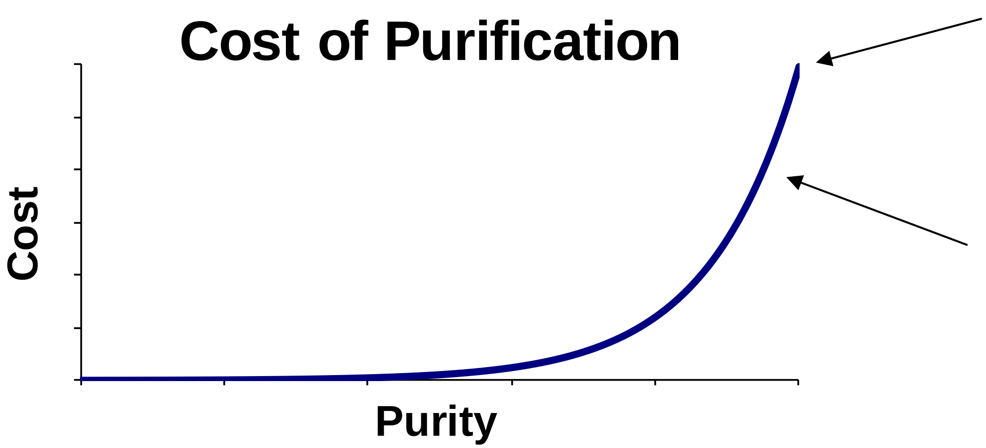


Brame J., V. Fattori, R. Clarke, Y. Mackeyev, L. J. Wilson, Q. Li and P.J.J. Alvarez (2014). Environmental Engineer and Scientist: Applied Research and Practice. 50(2), 40-46).

Need market-driven decrease ENM price



Few commercial applications
= low supply
→ prices stay high

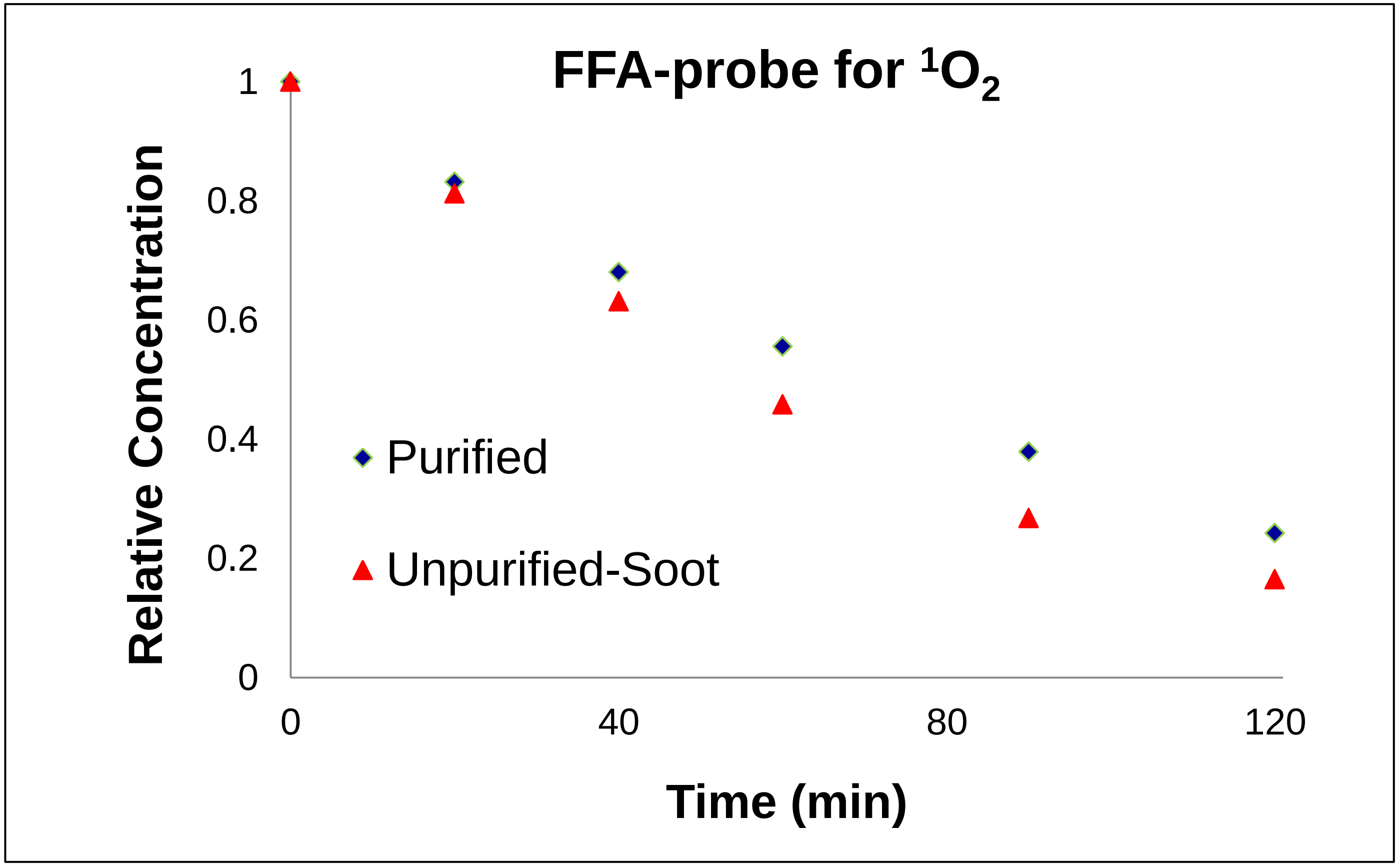


Most production is done for research (small quantities of highly purified material)

High purity requirements increase **separation cost** due to higher energy, solvent, & process time requirements

Avoid the diminishing returns of ultra high purity

Less pure amino-C_{60} cost less (20x) without significantly sacrificing reactivity



SUMMARY

- Low-energy desalination by nanophotonic MD or electrosorption
- DBP-free disinfection
- Advanced (photo)oxidation
- Selective nano-sorbents
- Multi-functional membranes
- Fouling- & corrosion-resistant surfaces

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

– Steve Jobs

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

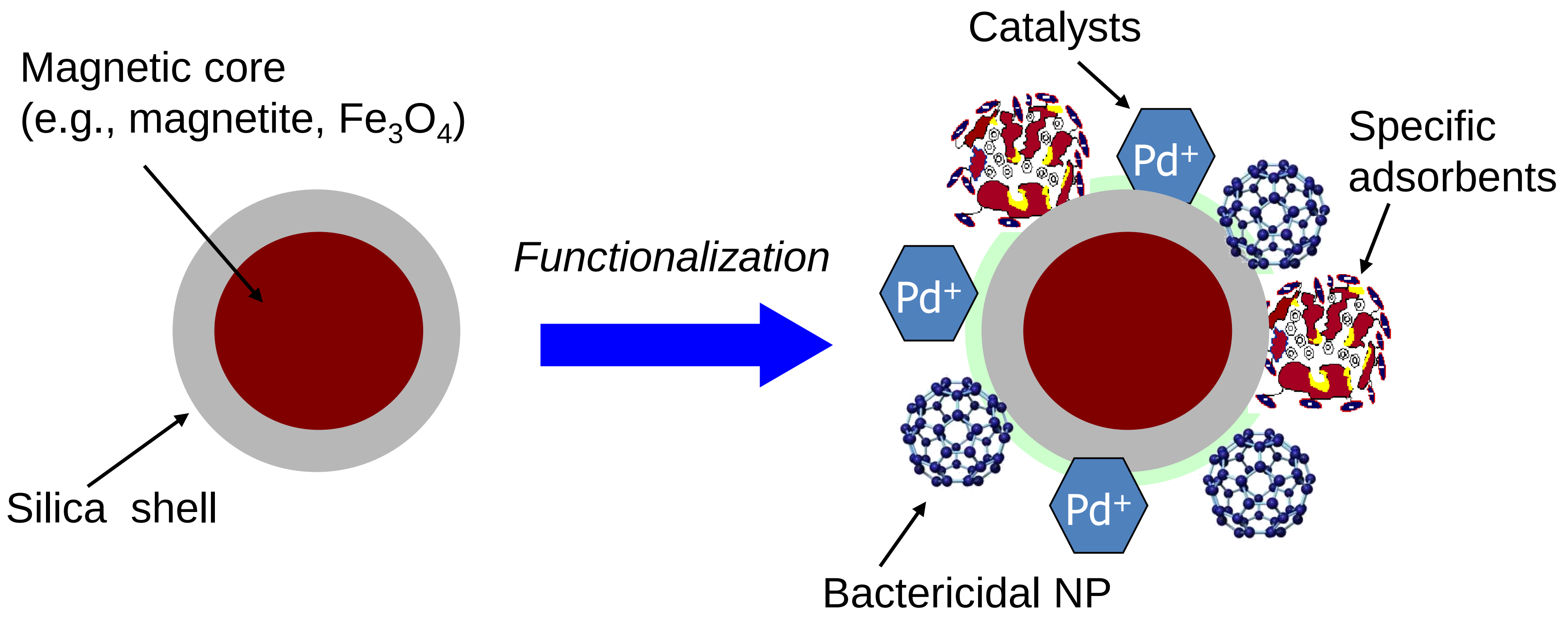
- Immobilize ENMs to minimize release and exposure and enable reuse (no free NPs)
- Model & monitor treated water for leaching
- Foster safety in manufacturing by iterating with OSHA on best practices
- Independent certification for meeting health & safety stds.

Drivers for Decentralized (Distributed) Treatment

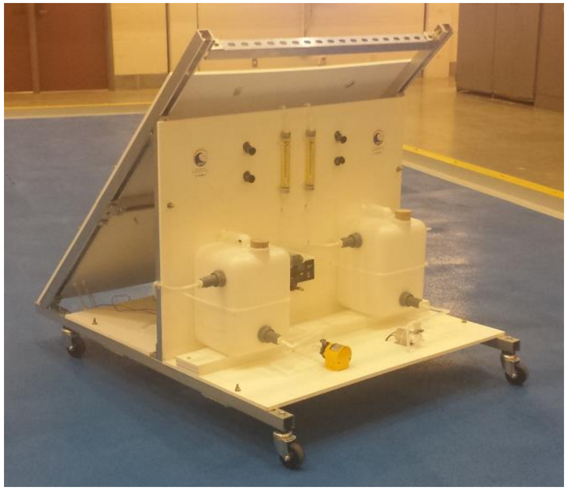
- Lack of adequate infrastructure (distribution systems, electricity)
- Match water supply with consumer location (avoid contamination during transport & storage)
- Reduce water losses and headloss in large and complex distribution systems.
- Reduce energy requirements

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

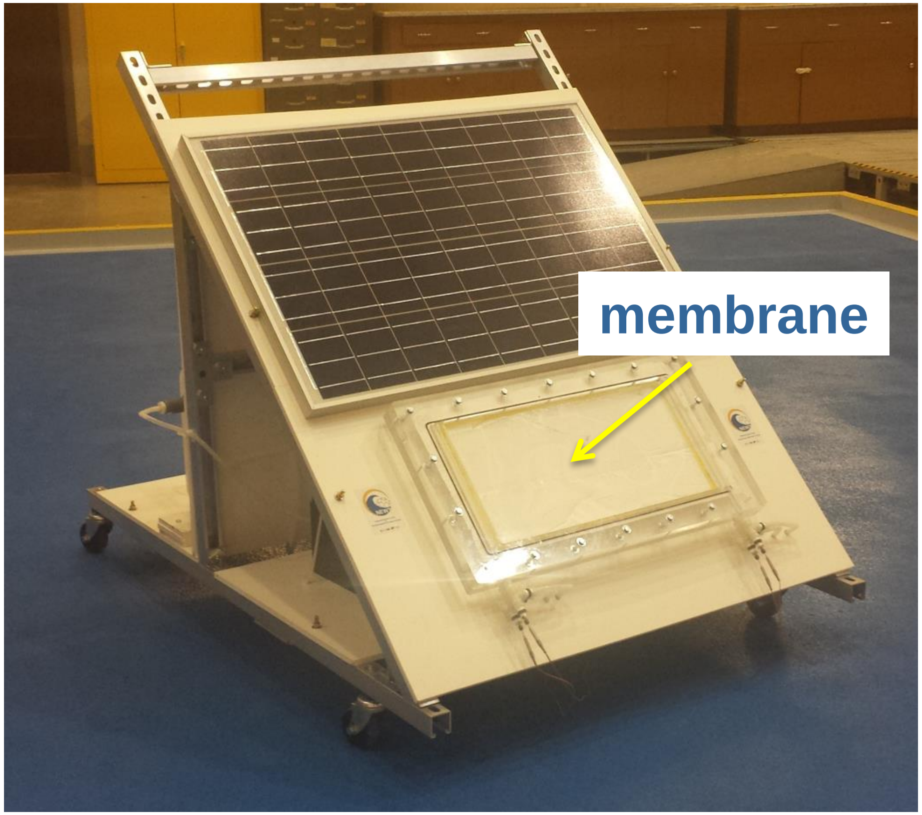


Pilot Solar MD



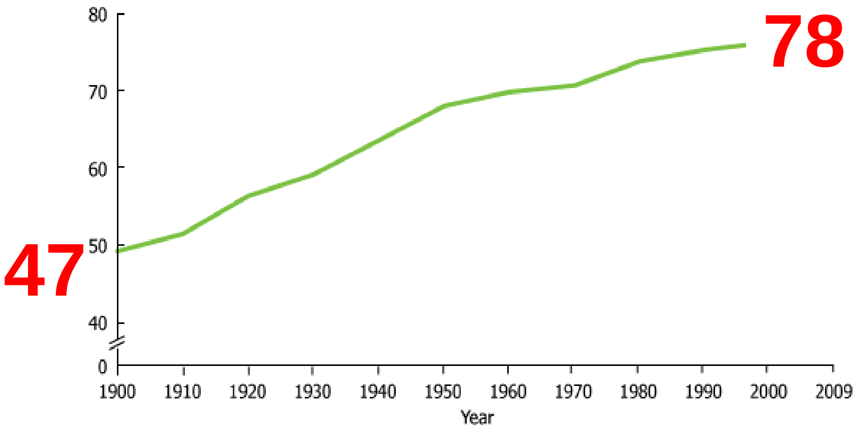
Built by Rice Undergraduates

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



NEWT Serves National Interests

American's life expectancy at birth



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

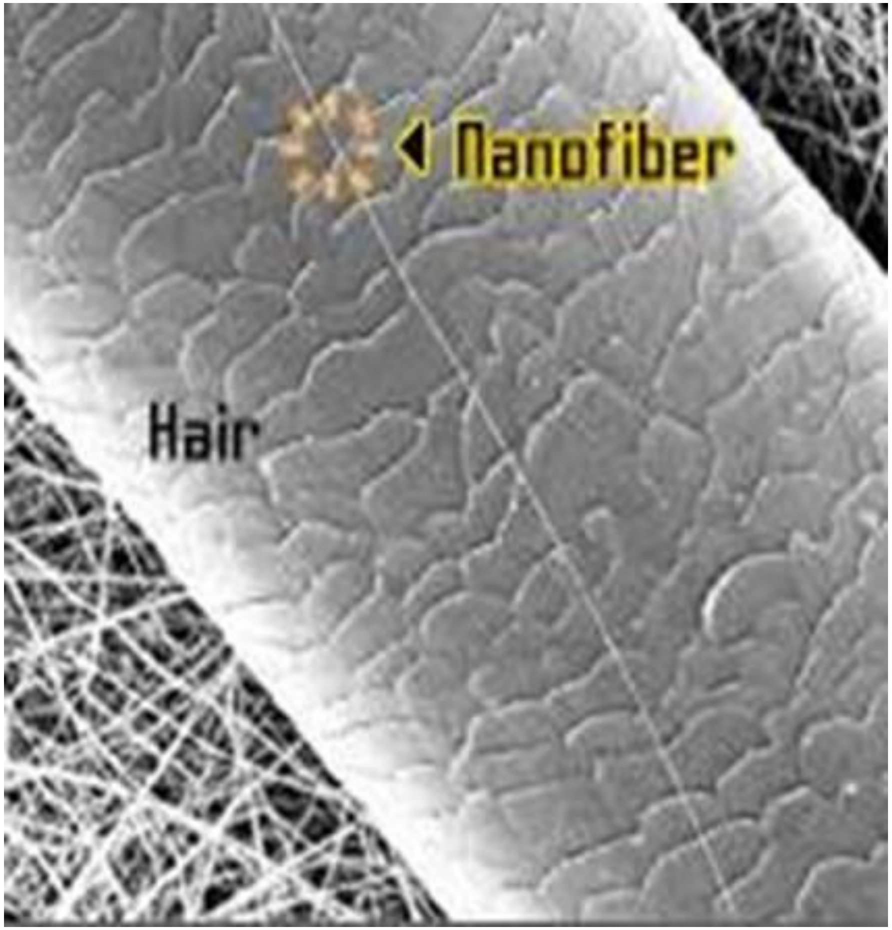
- Public health
- Energy production
- Food security
- Economic development

- 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

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



Operational Vision & Outcomes

APPLICATIONS AND OUTCOMES

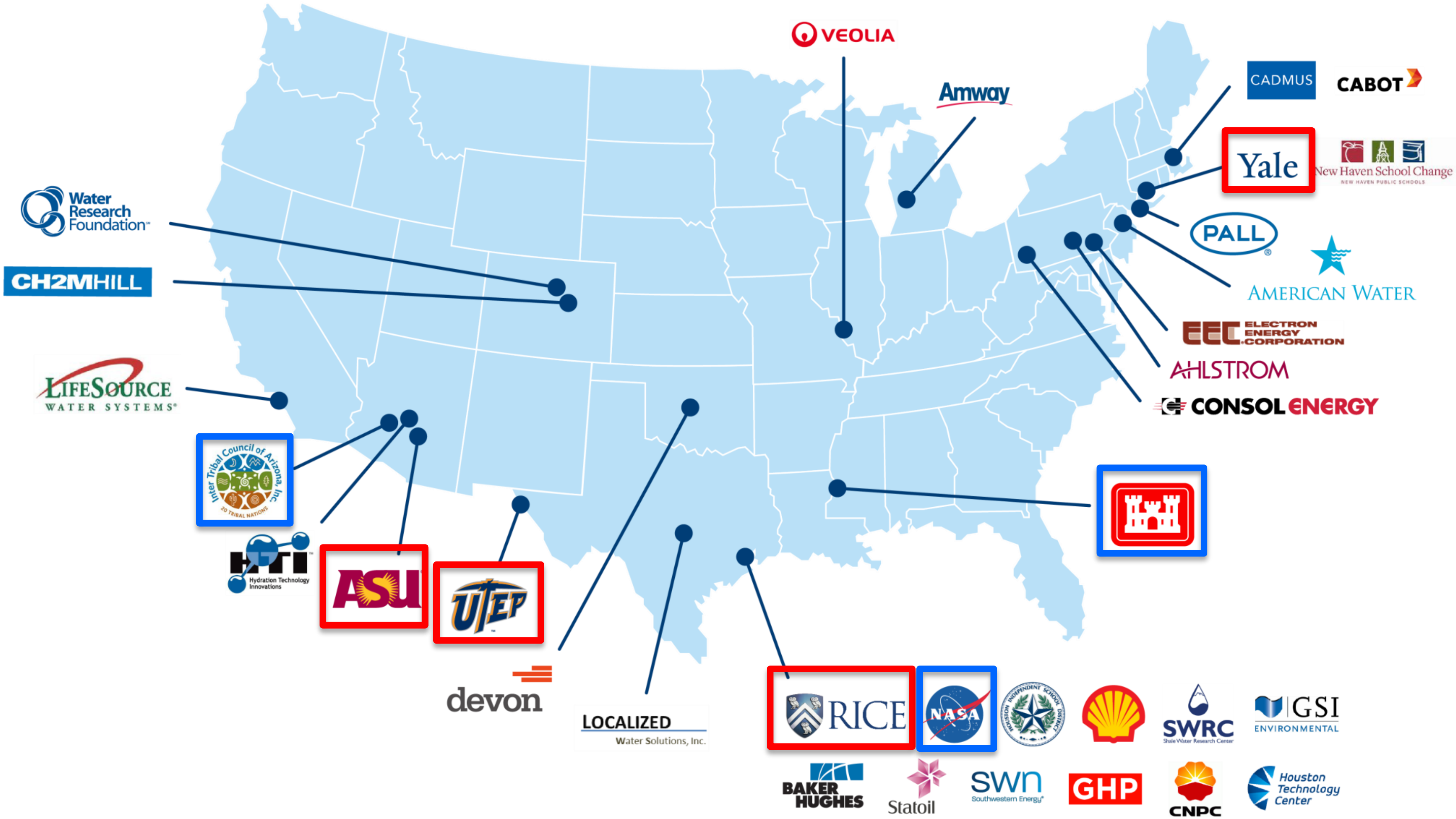
- Simple operation, low cost, humanitaran water supply (higher efficiency, lower energy requirements)
- Emergency water supply for disaster recovery
- Tailored water treatment in O&G fields

- Global health through safer water
- Renewable energy for water treatment and desalination
- Revitalization of water infrastructure
- O&G recovery with lower environmental impacts

- Globally competitive technology innovators and entrepreneurs
- Enhanced competitiveness of U.S. industries in the emerging markets of global health and water-energy nexus management and treatment

BASIC SCIENCE AND DISCOVERY ▶ TECHNOLOGICAL INNOVATION ▶ COMMERCIALIZATION AND ECONOMIC DEVELOPMENT

Some of Our NEWT Partners



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

NEWT is Supported by Experienced Partners Across the Value Chain

Nanomaterial and advanced material manufacturers

EEC Electron Energy Corporation · CABOT · HTI Hydration Technology Innovations · Purifics

Equipment manufacturers

AHLSTROM · Amway · LifeSource Water Systems · PALL

Research, development and deployment partners

NASA · NSF · CADMUS · GHP · Houston Technology Center · UNESCO · Water Research Foundation · wetsus

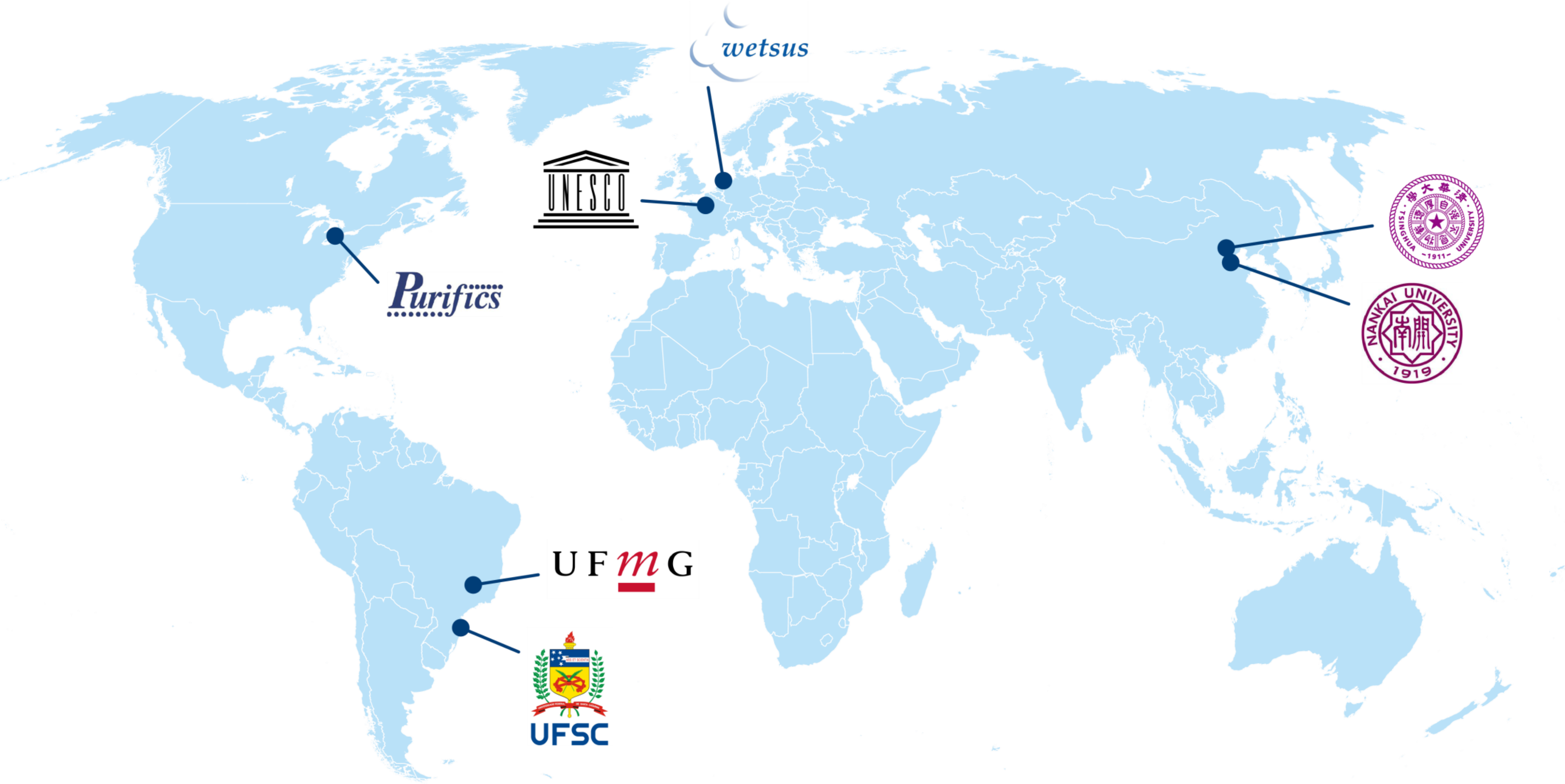
Service providers

American Water · Baker Hughes · CH2MHILL · GSI Environmental · Localized Water Solutions, Inc. · SWRC Shale Water Research Center · VEOLIA

End users

CNPC · CONSOL Energy · devon · swn Southwestern Energy · Statoil · Inter Tribal Council of Arizona, Inc. 20 Tribal Nations

International Partners



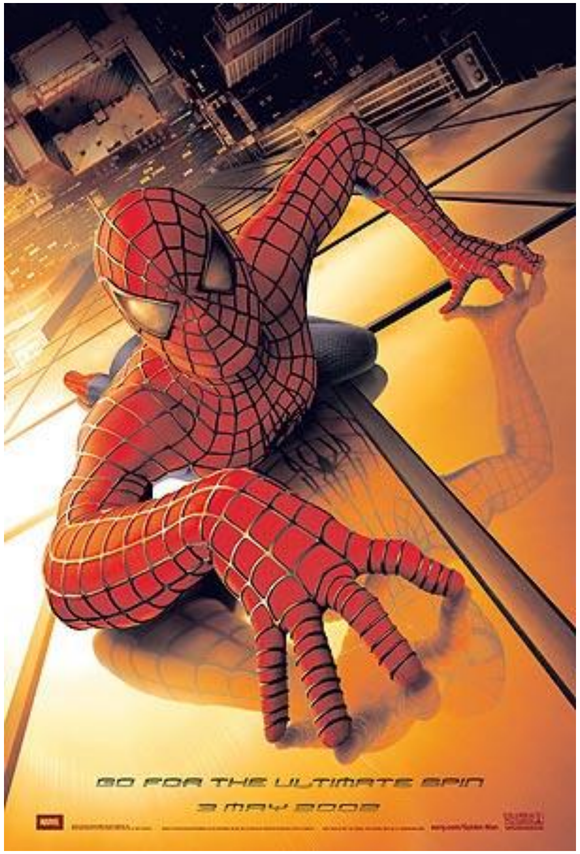
- Co-development and production of advanced multifunctional materials
- Globally-relevant research and education experiences for students
- Testbed sites for applications in fast-growing water markets

Responsible Nanotechnology

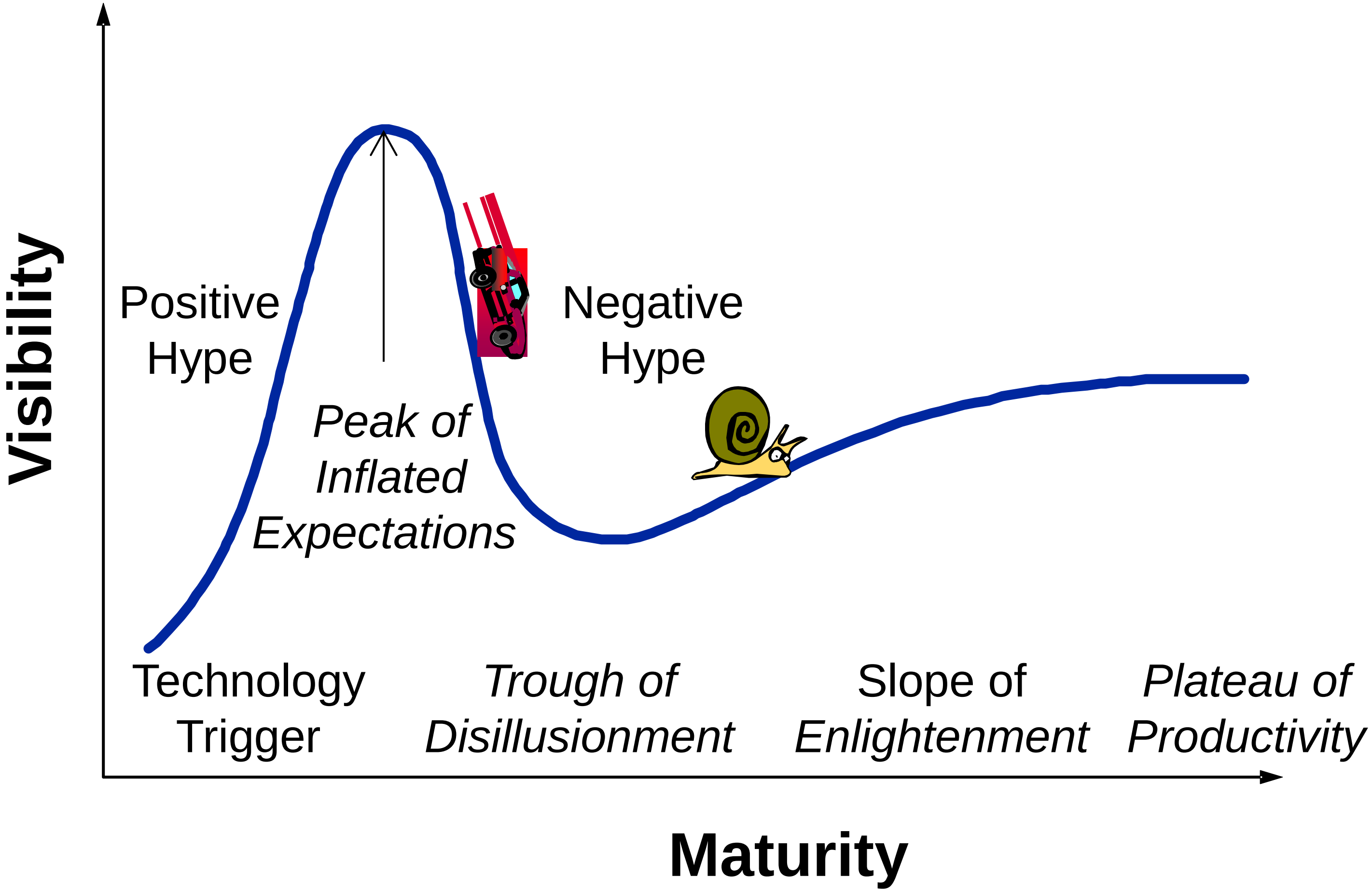
"With Great Power, Comes Great Responsibility"

Uncle Ben to Peter Parker in Spider Man

Paul Hermann Muller
Thomas Midgley

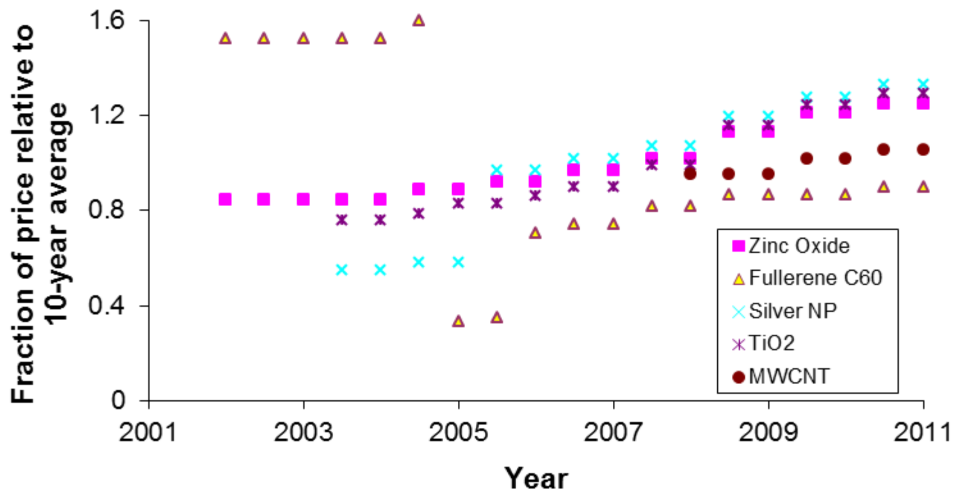


Quo Vadis, Nano?



"Nanohype" - Berube

Need market-driven decrease ENM price



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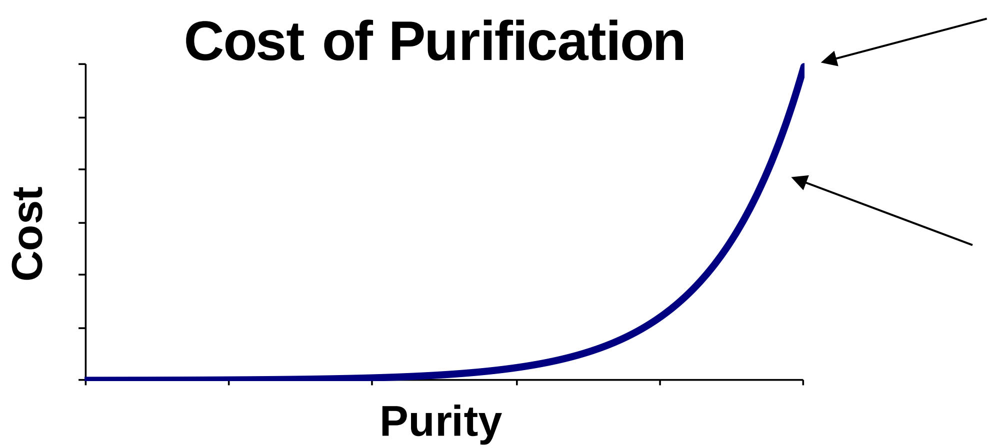

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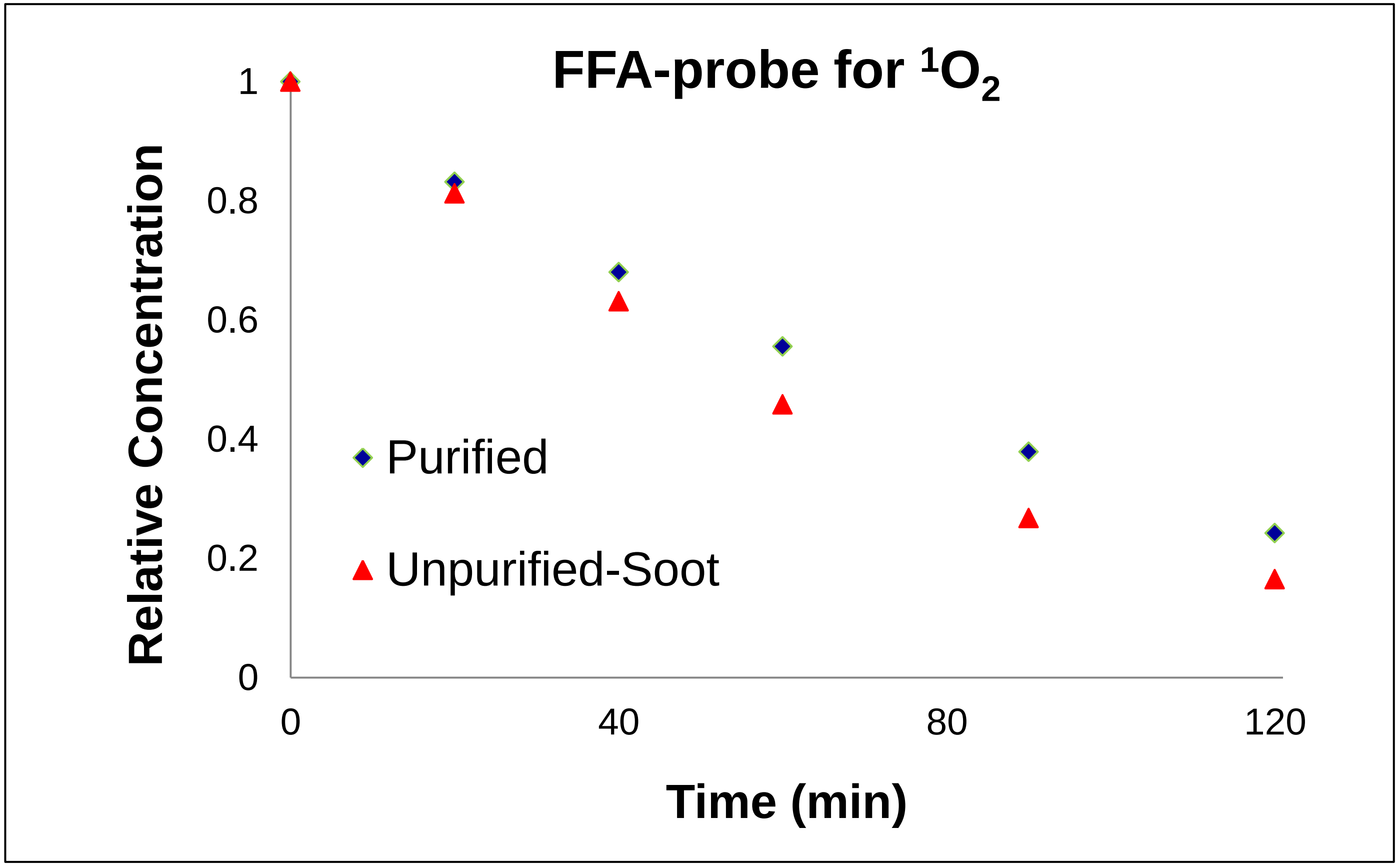


LAUDATO SI'

"We are the beneficiaries of two centuries of enormous waves of change…and, more recently, the digital revolution, robotics, biotechnologies and *nanotechnologies*. It is right to rejoice in these advances and to be excited by the immense possibilities which they continue to open up before us, for 'science and technology are wonderful products of a God-given human creativity."

Plate-and-Frame Configuration

- Thin, patterned transparent poly(methyl methacrylate) sheet serves simultaneously as the top plate of the module, the optical window and the spacer that forms the feed flow channels.
- Mount it on a solar tracker to maximize sunlight collection.

http://www.wassertech.net/content/view/34/29/lang,thai/

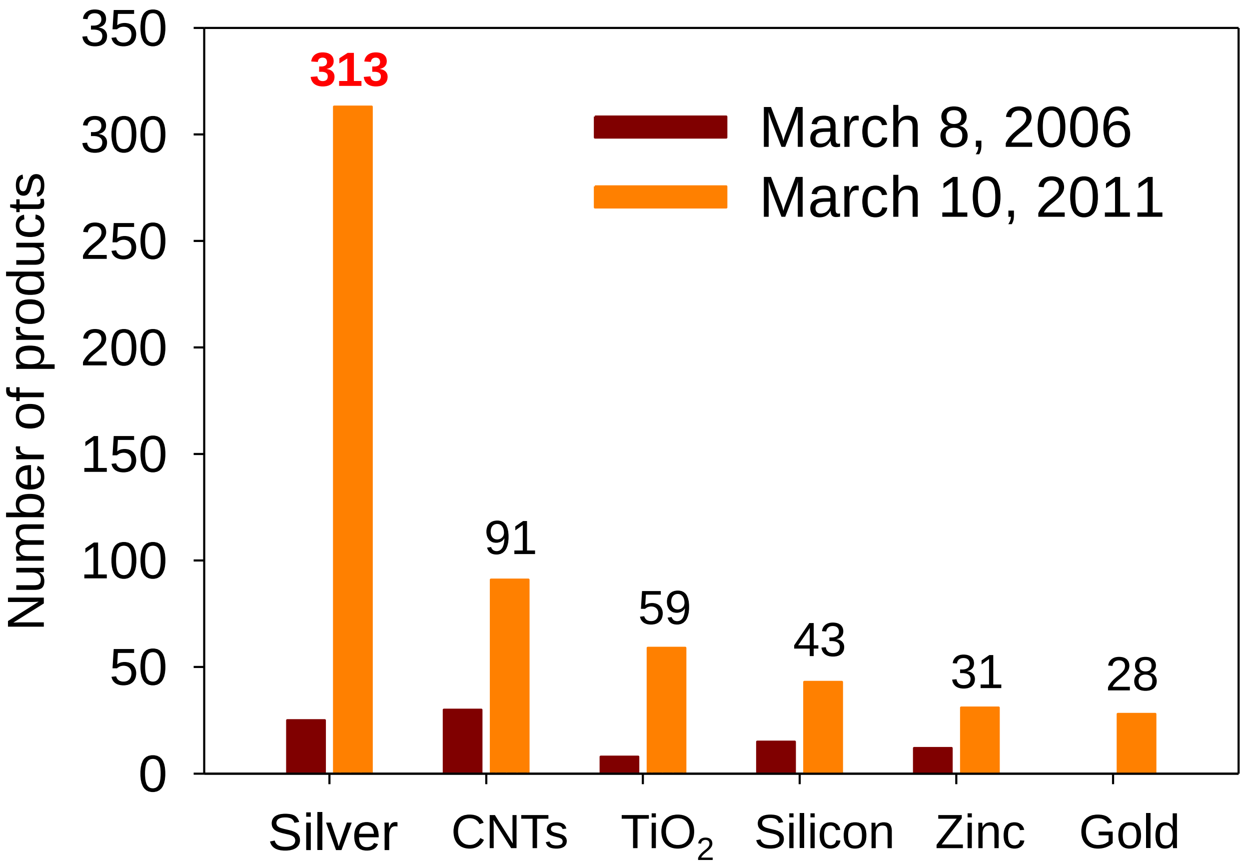
Risk = Hazard × Exposure

Hazard, but no exposure

Exposure but no hazard

Hazard as well as exposure

Example: Silver Nanoparticles



Most Widely Used Nanomaterials In Commercial Products

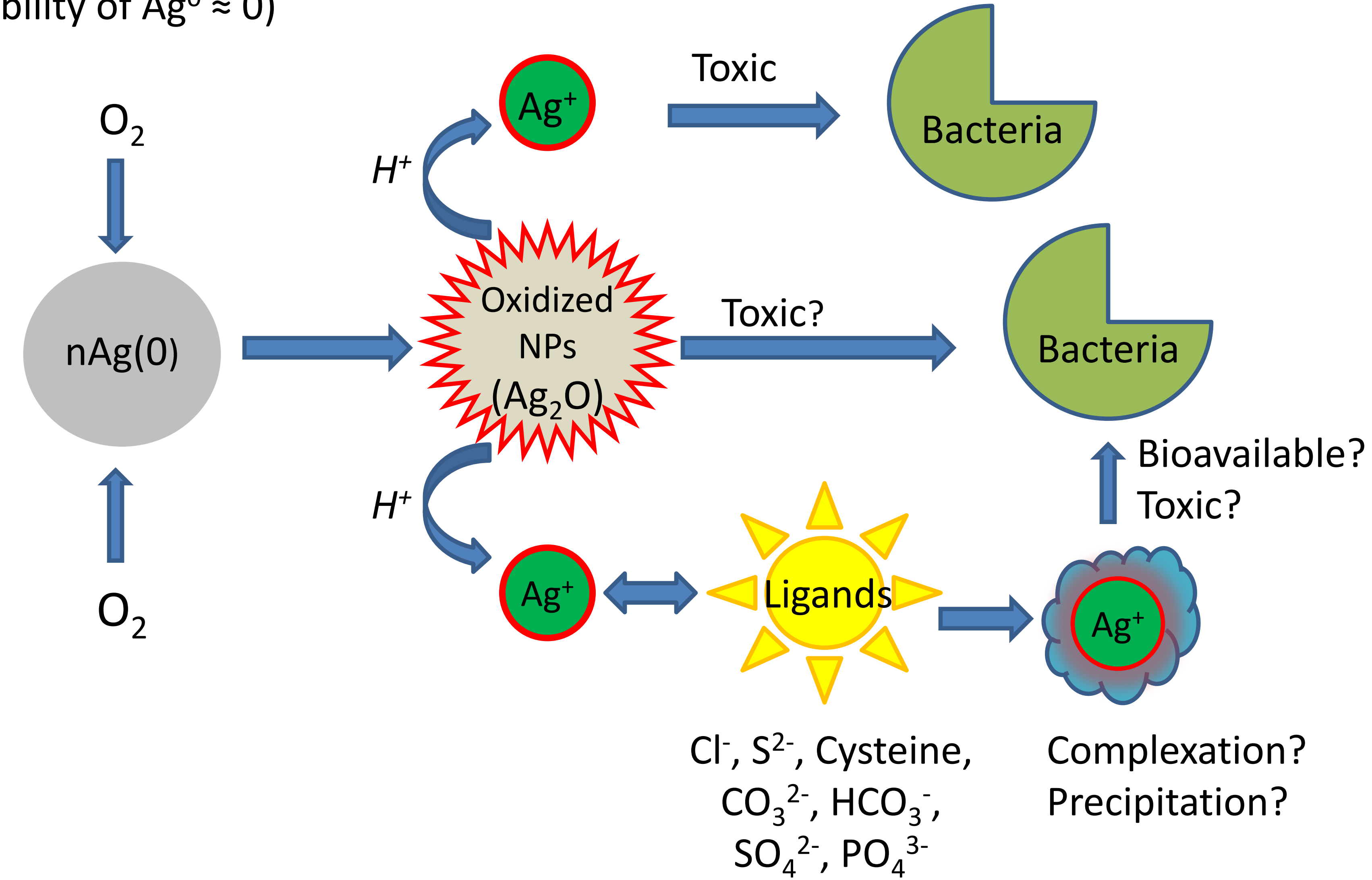
Source: Woodrow Wilson-The project on emerging nanotechnologies

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

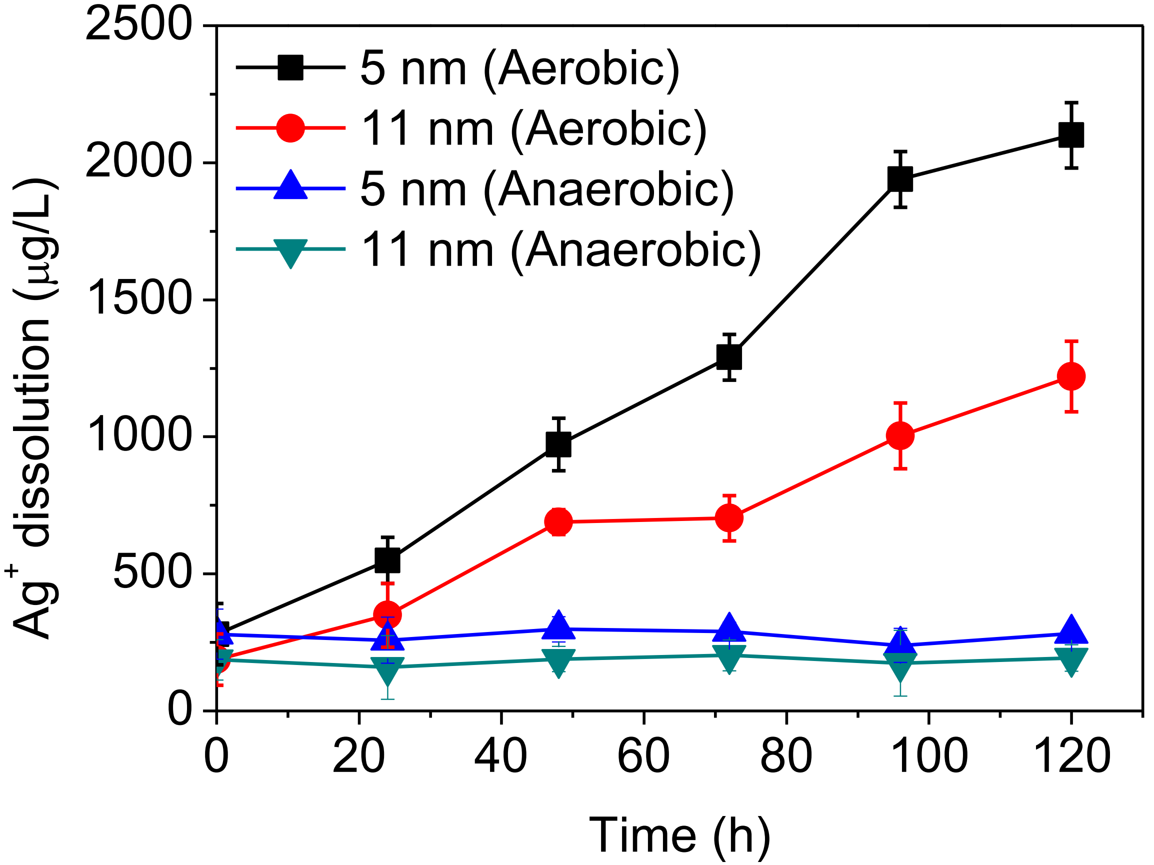
- And how do environmental conditions affect their relative influence?

Bioavailability and Toxicity of AgNPs

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

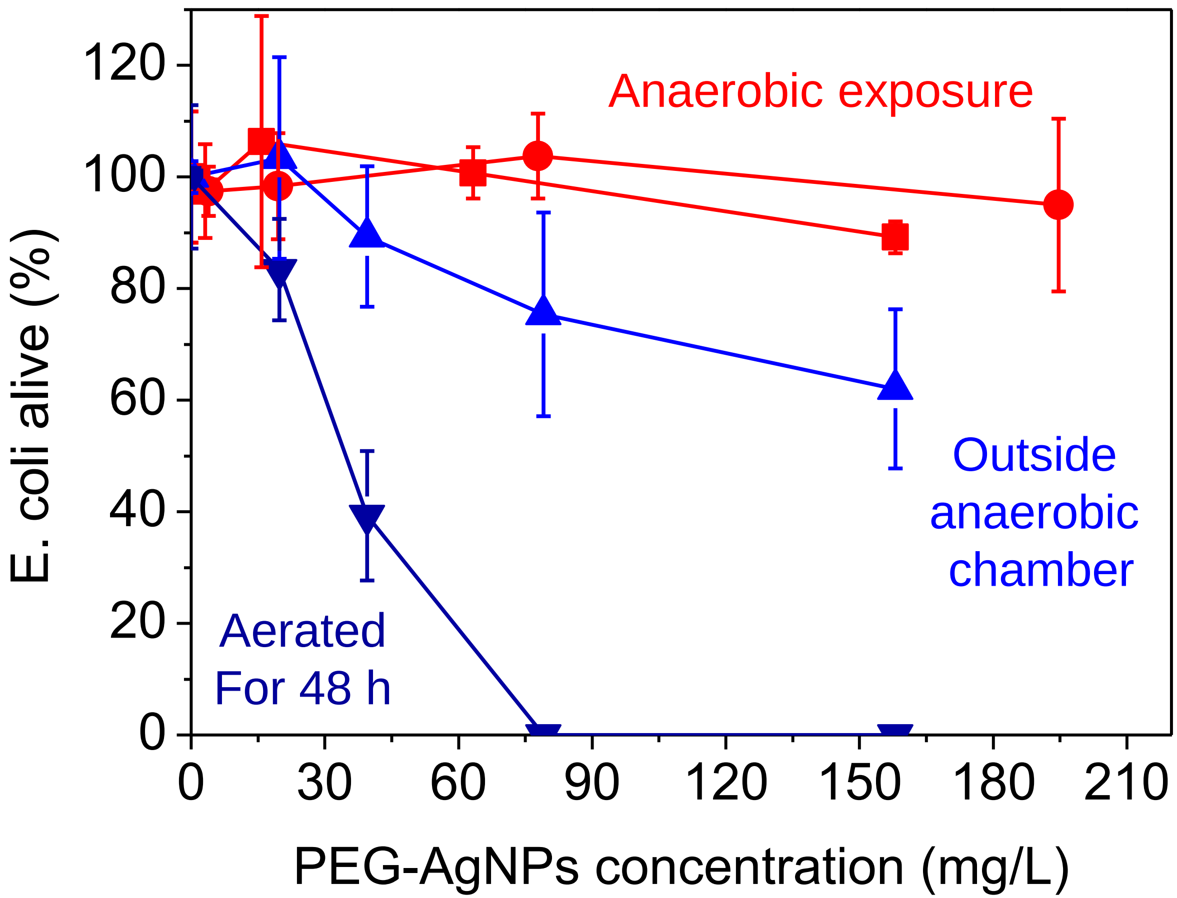


No Ag^+ release under Anaerobic Conditions
(Faster release for air-exposed smaller particles)



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



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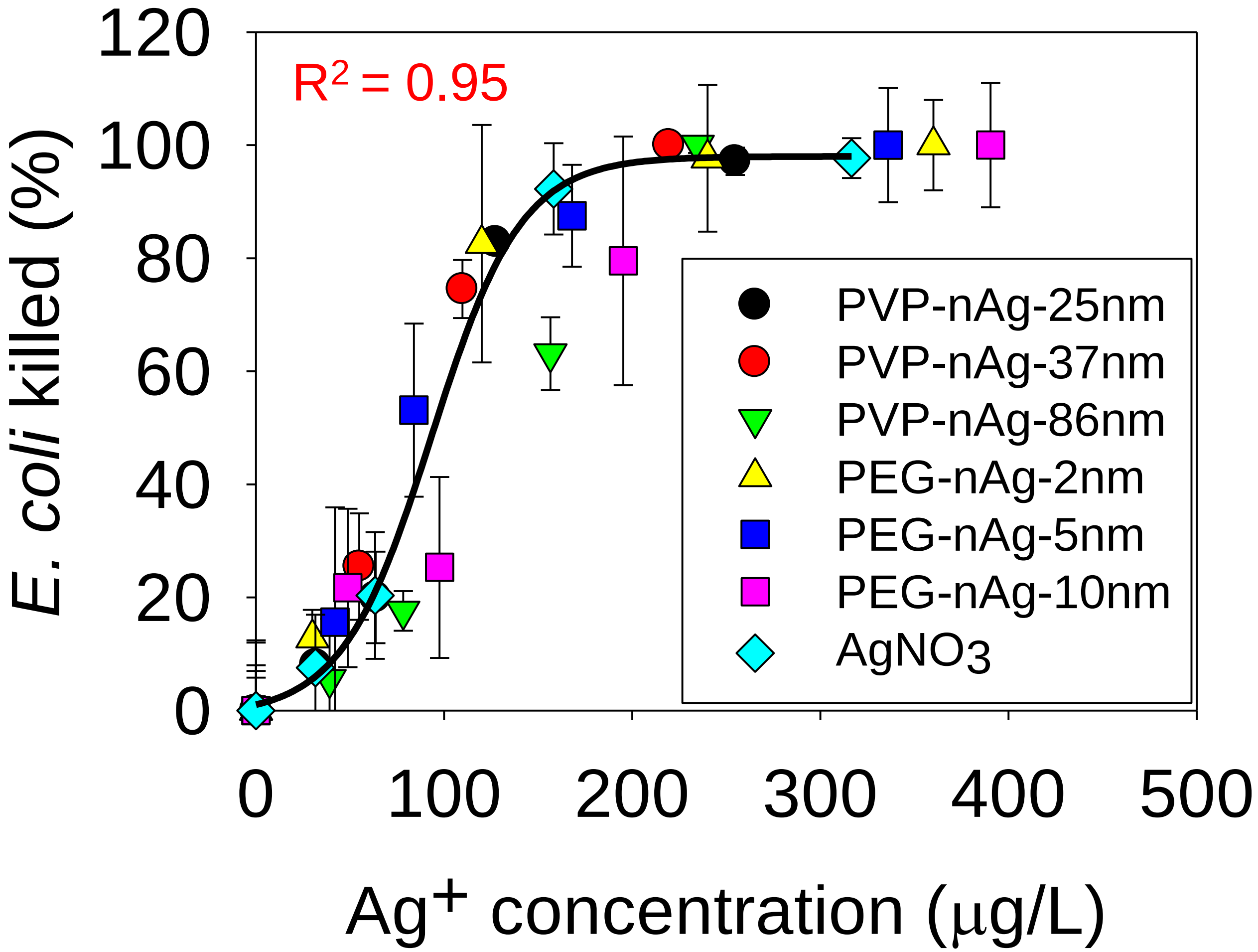
AgNP Toxicity Can Be Explained by Dose-Response of Released [Ag^+]



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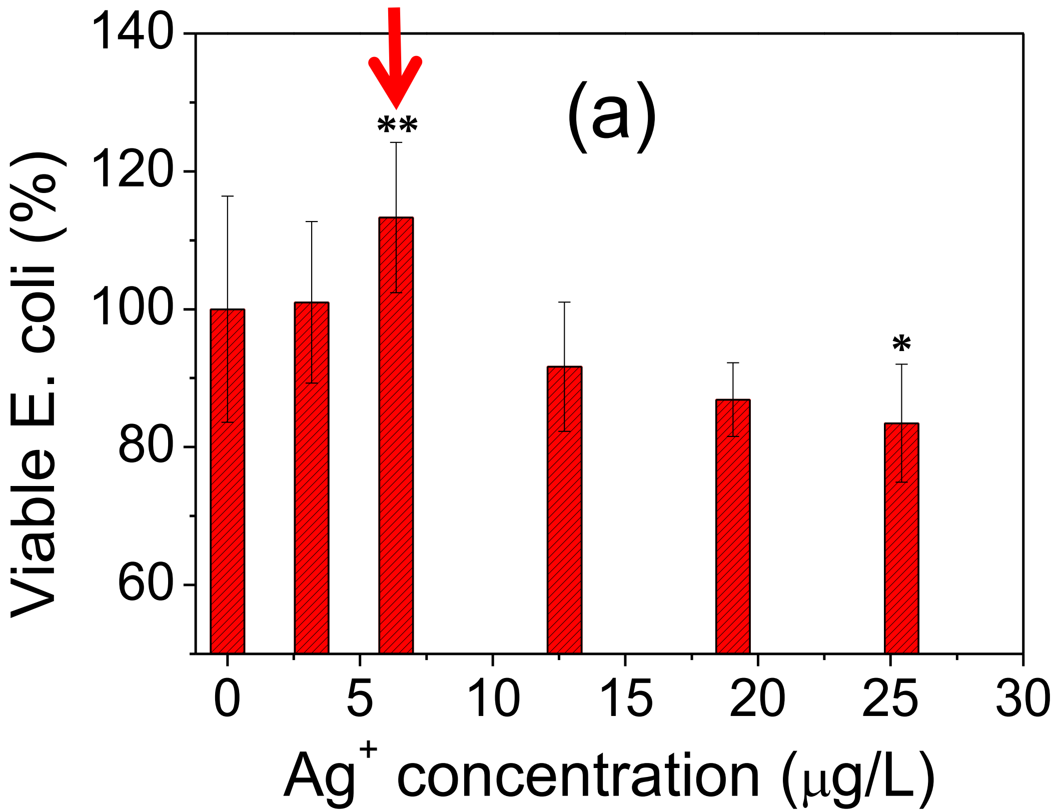
“What does not kill you makes you stronger”

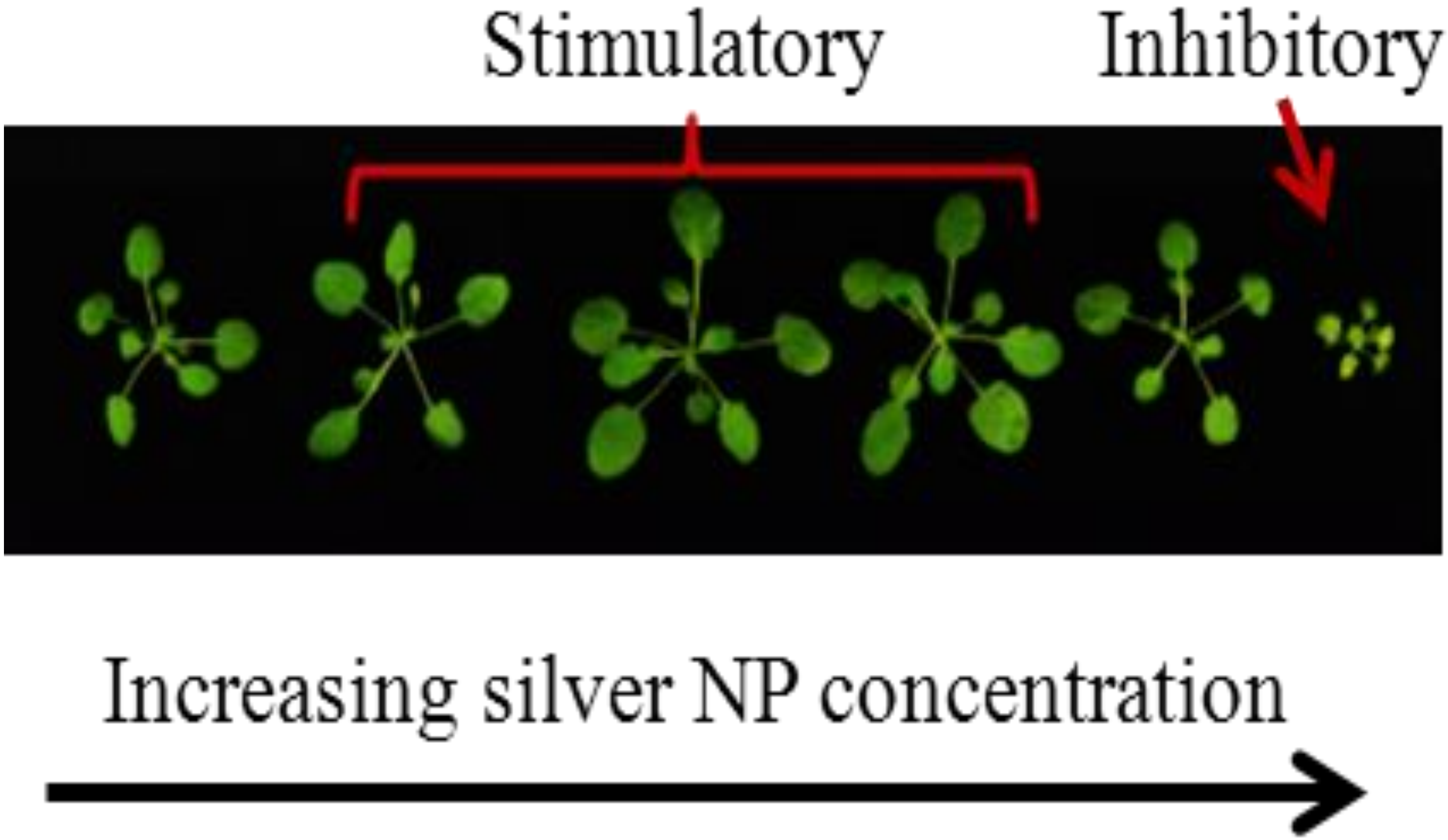
Friedrich Nietzsche



Stimulatory effect after 6 h exposure to low Ag^{+} concentration **(Hormesis?)**

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

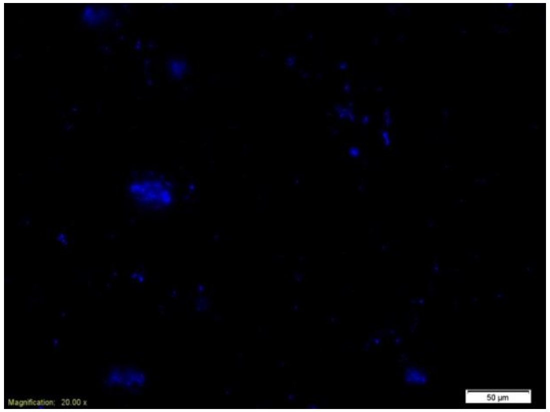
Sub-Lethal Concentrations of AgNPs Could Also Stimulate Plants

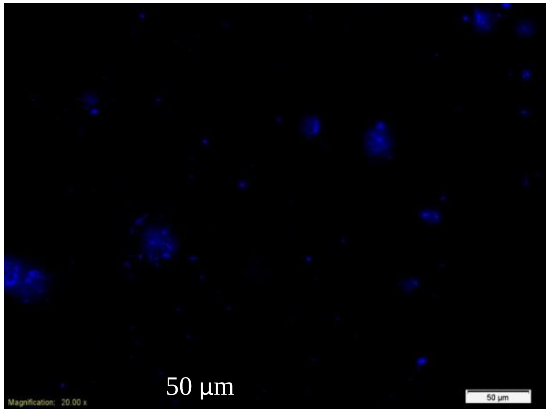


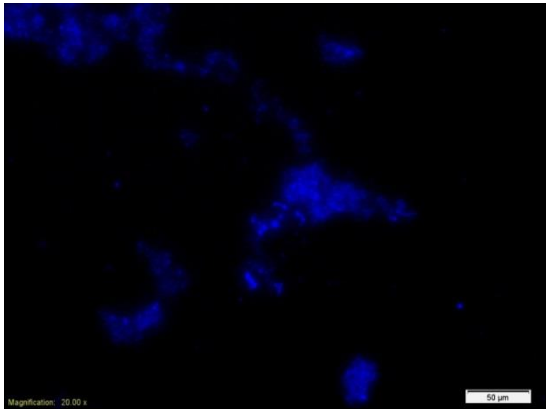
Wang J., Y. Koo, A. Alexander, Y. Yang, S. Westerhof, Q. Zhang, J. Schnoor, V. Colvin, J. Braam, and P.J. Alvarez (2013). Environ. Sci. Technol. 47 (10): 5442–5449.

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

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







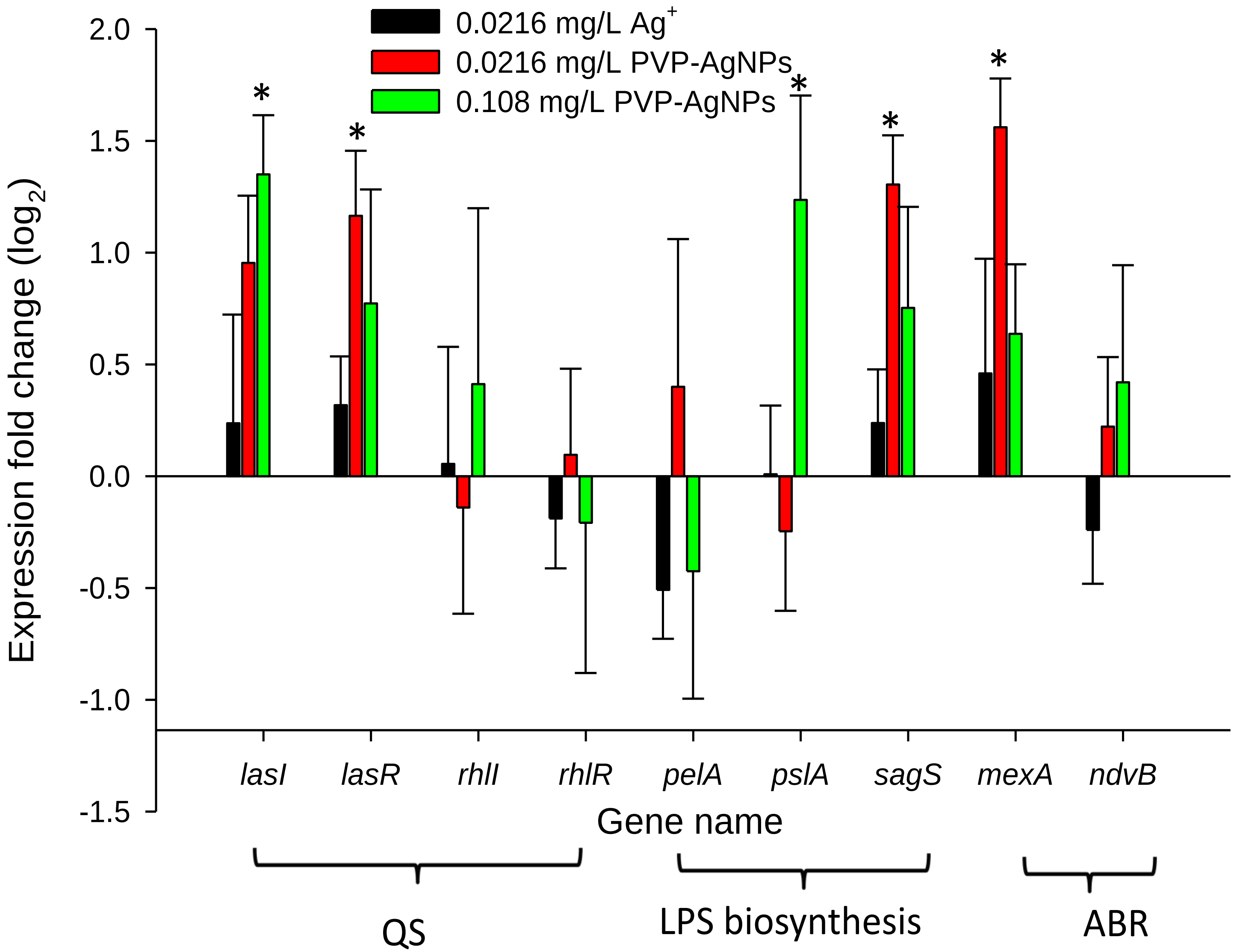
Control

0.02 mg/L of Ag^{+}

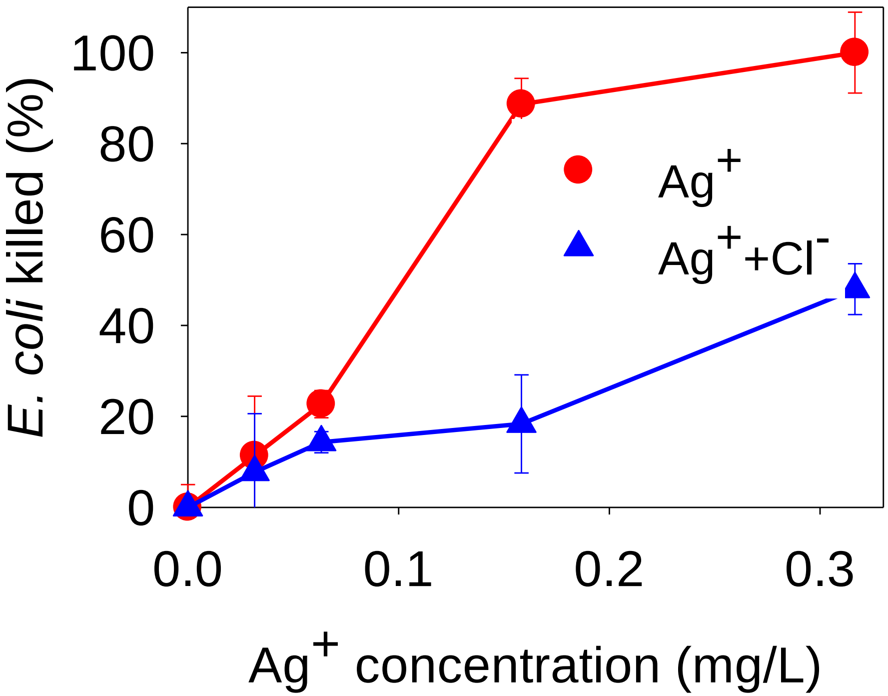
0.02 mg/L of AgNPs

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

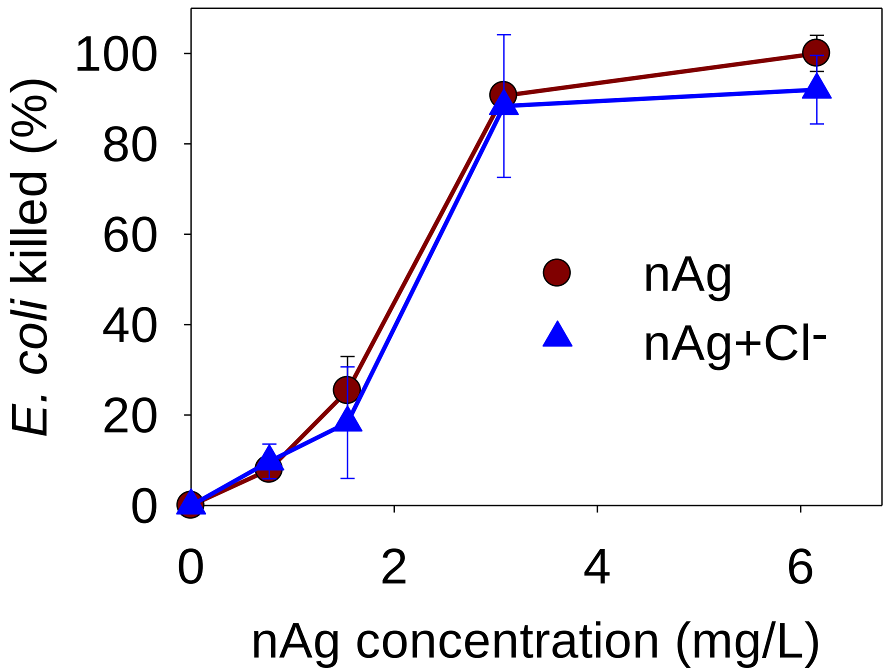
Sub-lethal Exposure of PAO1 to AgNPs also Upregulates Quorum Sensing, LPS, and Antibiotic Resistance Genes



Why is nAg sometimes a stronger bactericide?



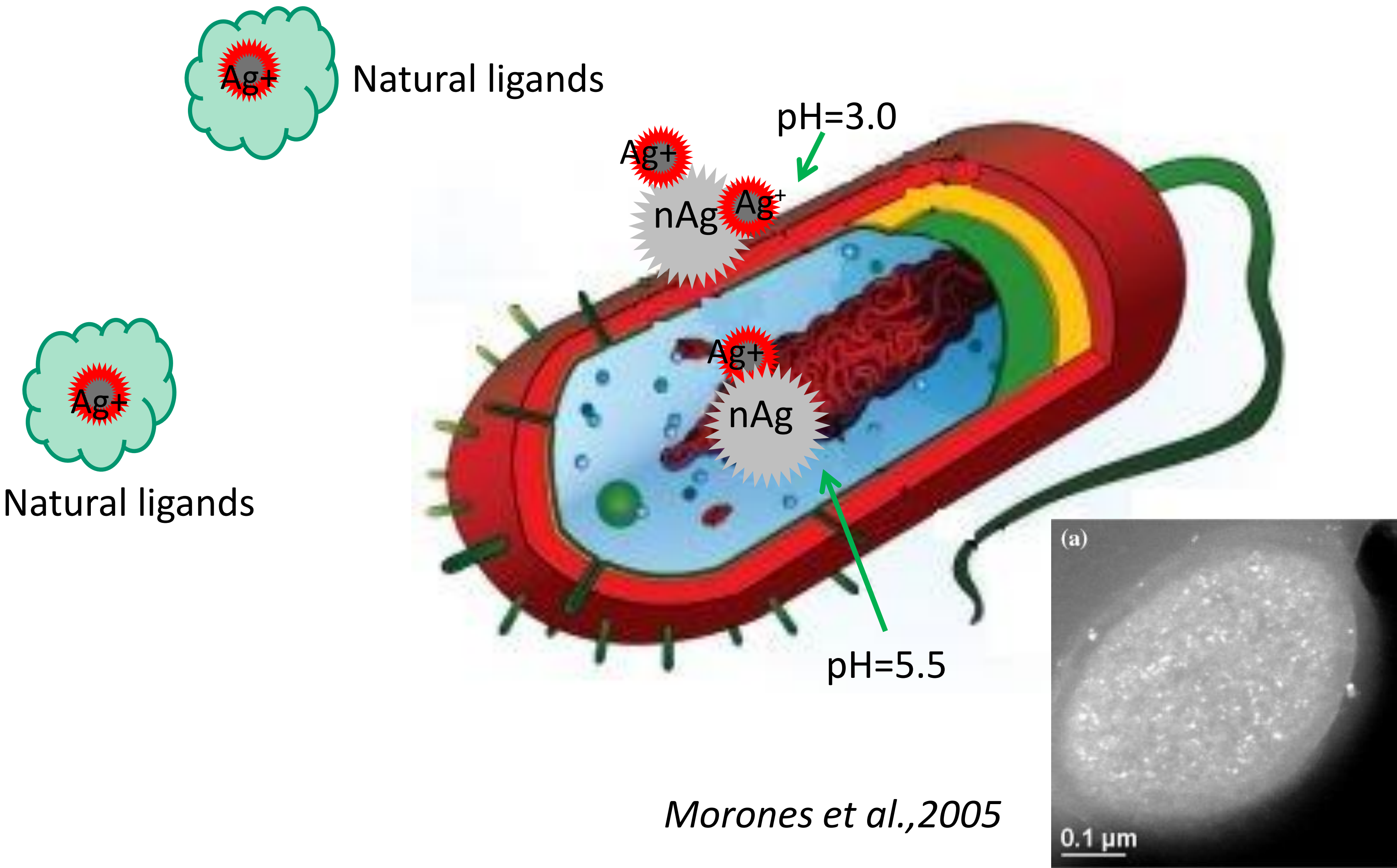
Max [Ag^+]: 3µM; [Cl^-]: 3µM



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

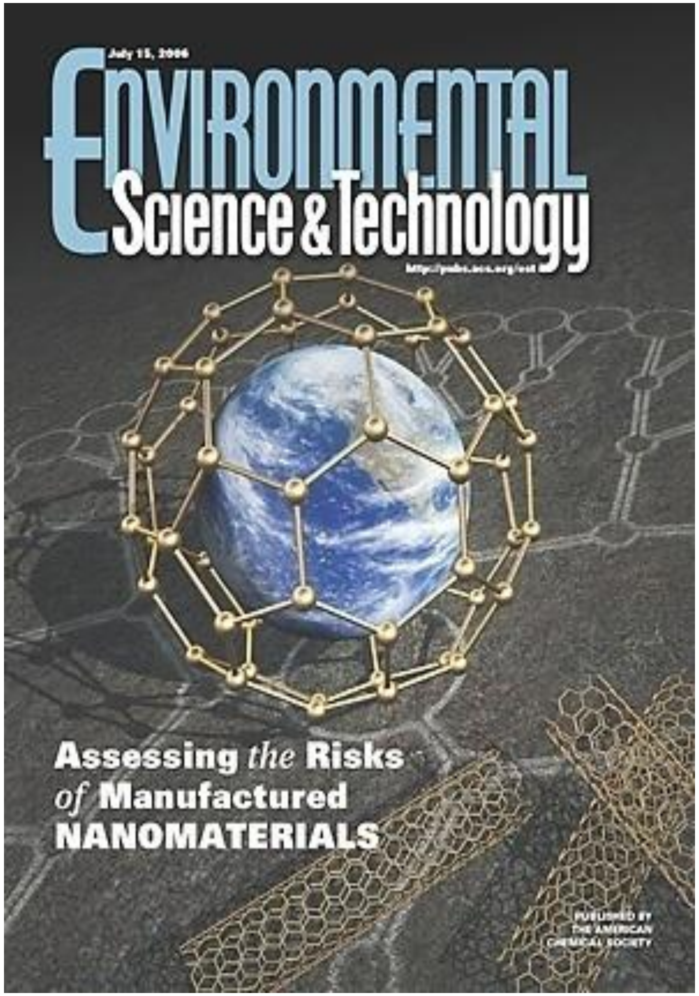


Morones et al.,2005

CONCLUSIONS

- Implications: Ecotoxicology- Ecosystem services (primary productivity, food webs, nutrient cycling?) biodiversity? Toxicity to higher organisms? *Mitigated by NOM, salts*

- Applications: DBP-free disinfection, advanced (photo) oxidation processes, anti-fouling/corrosion coatings? functionalized membranes



Outlook for Developing Nations

Despite current barriers (technical capacity, cost) the use of ENMs will increase in developing nations *(similar to cell phones)* for point-of-use water treatment and reuse, due to:

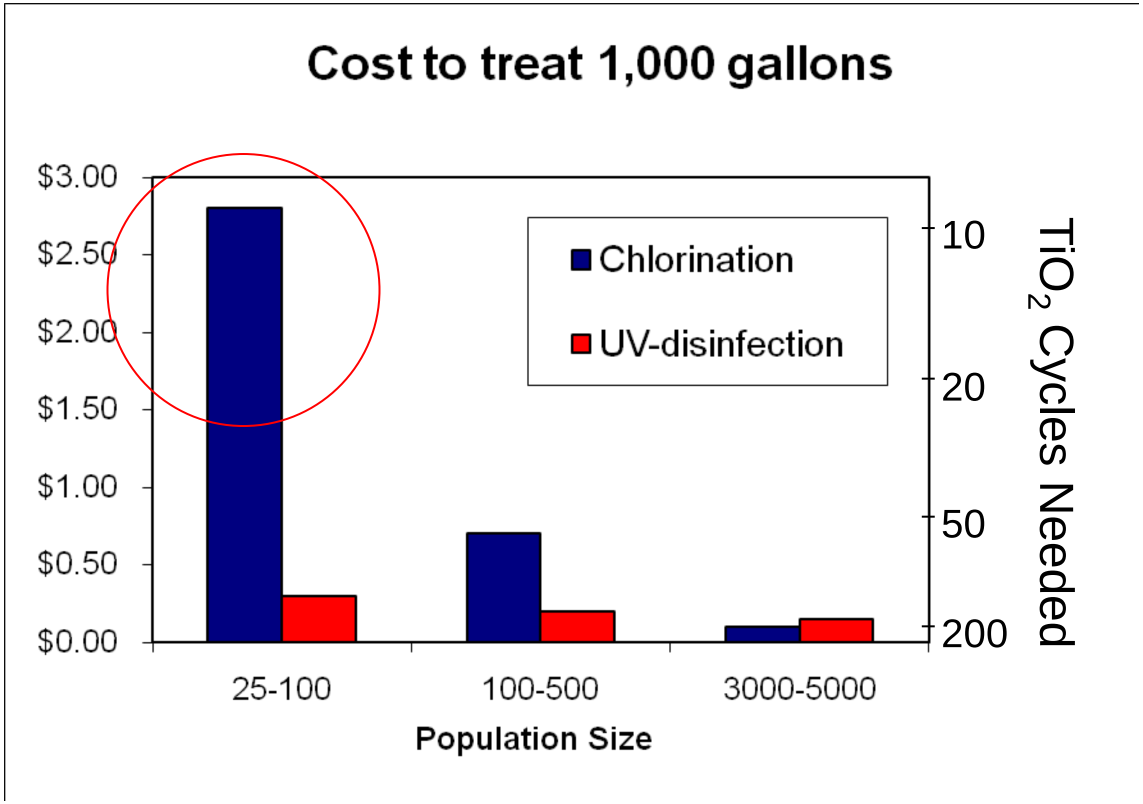
- Decreasing cost:
  - *Economy of scales*
  - *Recyclability of immobilized NPs*
  - *Avoid diminishing returns of ultra high purity*
  - *Valuable properties imparted at low additive ratios*
- Savings on capital investment for new infrastructure in expanding mega-cities

When Does NEWT Make Sense?

- Where current technologies **do not meet** current or upcoming DWT or WWT **regulations**;
- To treat **recalcitrant compounds** (e.g., pharmaceuticals) that escape WWTPs and hinder reuse (e.g., irrigation);
- Where there is **insufficient infrastructure** and one must rely on POU devices
- When NEWT **enhances cost-effectiveness** (e.g., faster, less energy, and less material)

Feasibility Is within Reach

(Photo-disinfection with TiO_2 is feasible for small villages if recycled)



Recycling makes photo-disinfection with TiO_2 competitive with traditional treatment processes *at small scales*

(Assumes $0.15/g TiO_2, 50 g/L used for treatment)

Nanosystems Engineering Research Center for

Nanotechnology-Enabled Water Treatment

NEWT

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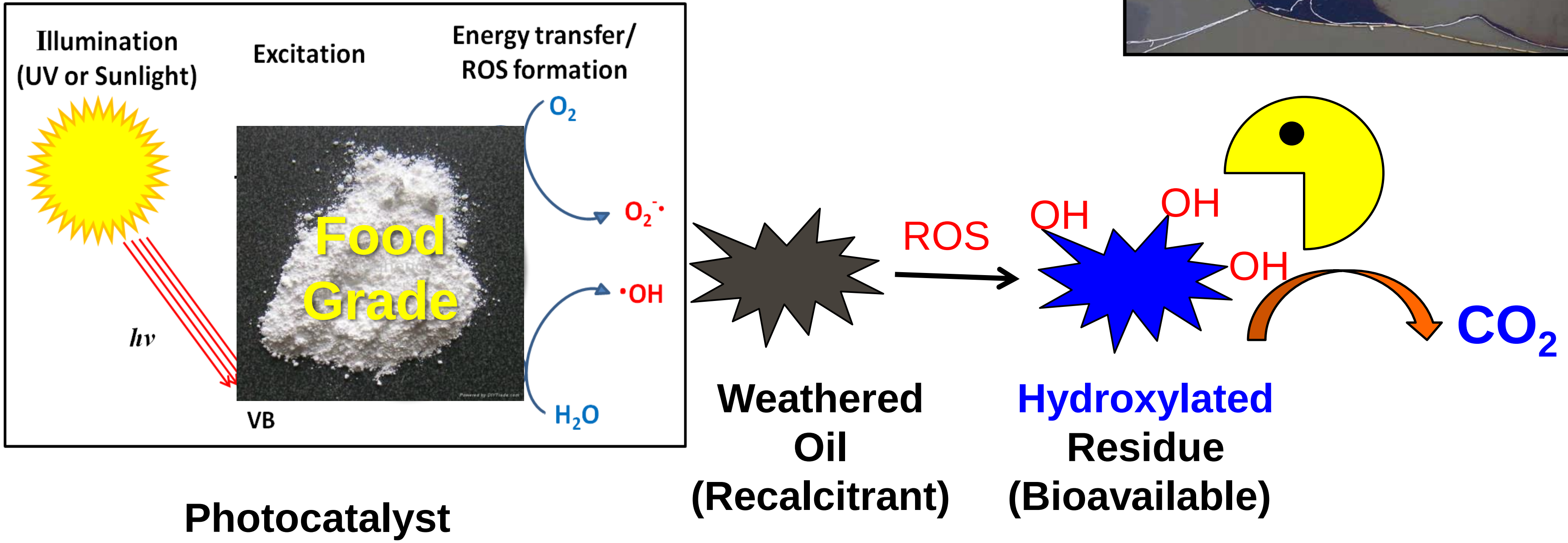
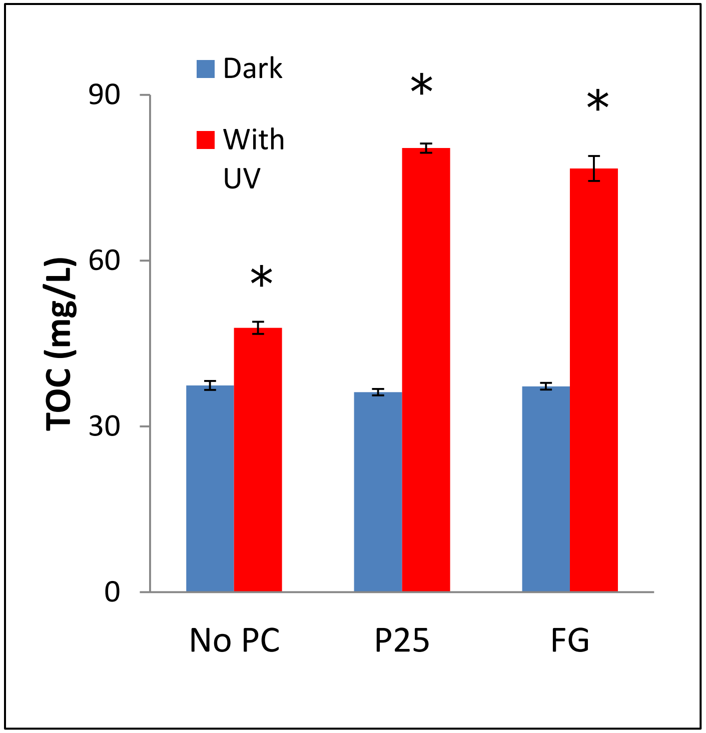
www.newtcenter.org

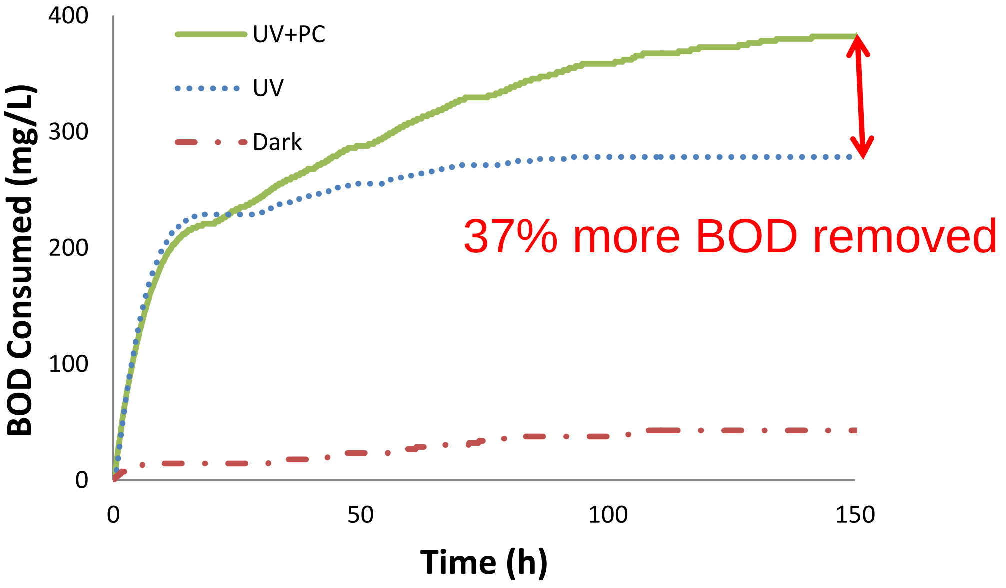
RICE ASU UTEP Yale

Photocatalytic Hydroxylation of Weathered Oil to Enhance Bioavailability and Bioremediation



Photocatalysis Increased Solubilization and Biodegradation of Weathered Oil

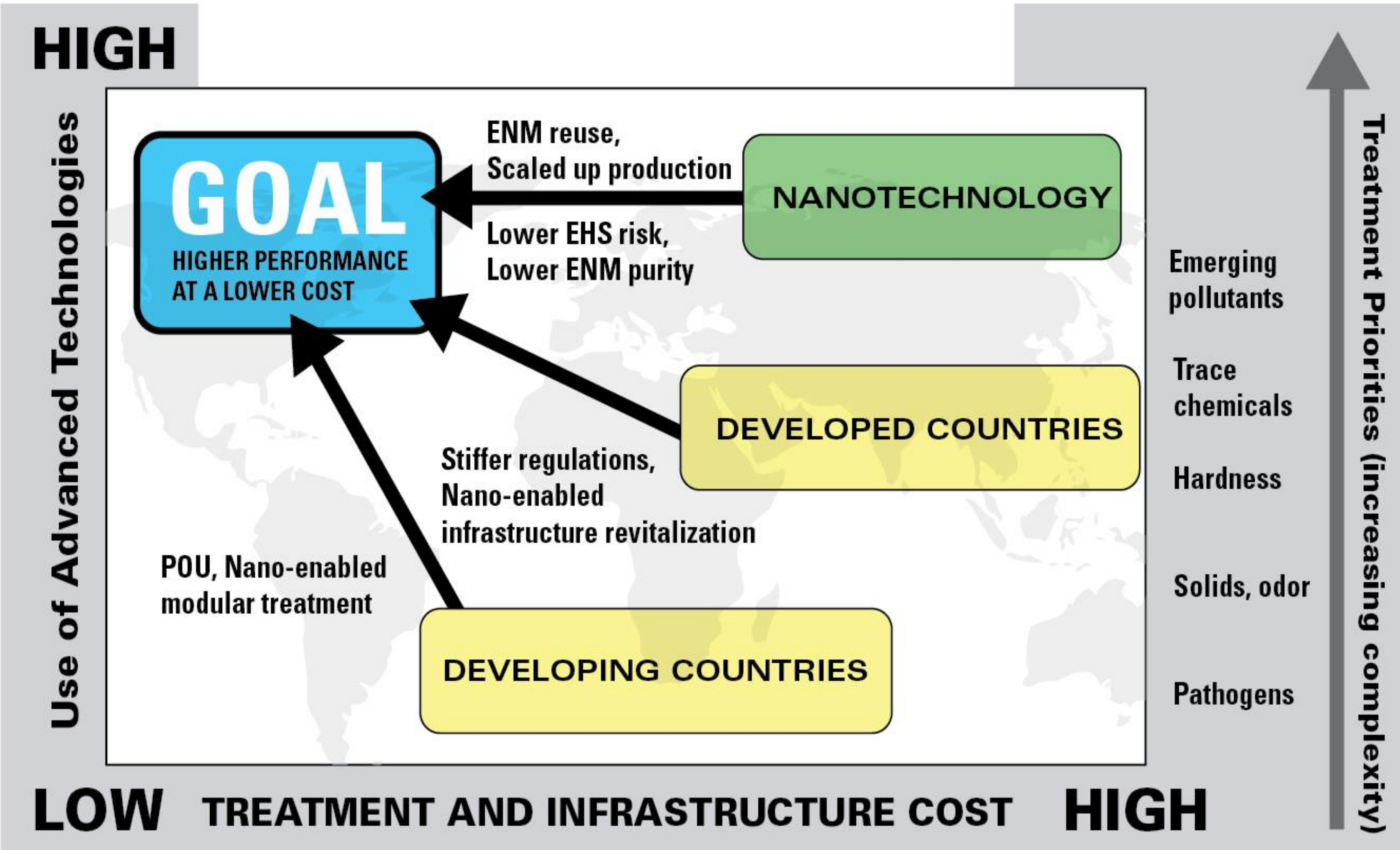




* statistically significant (*p* <0.05) after 1-day exposure

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

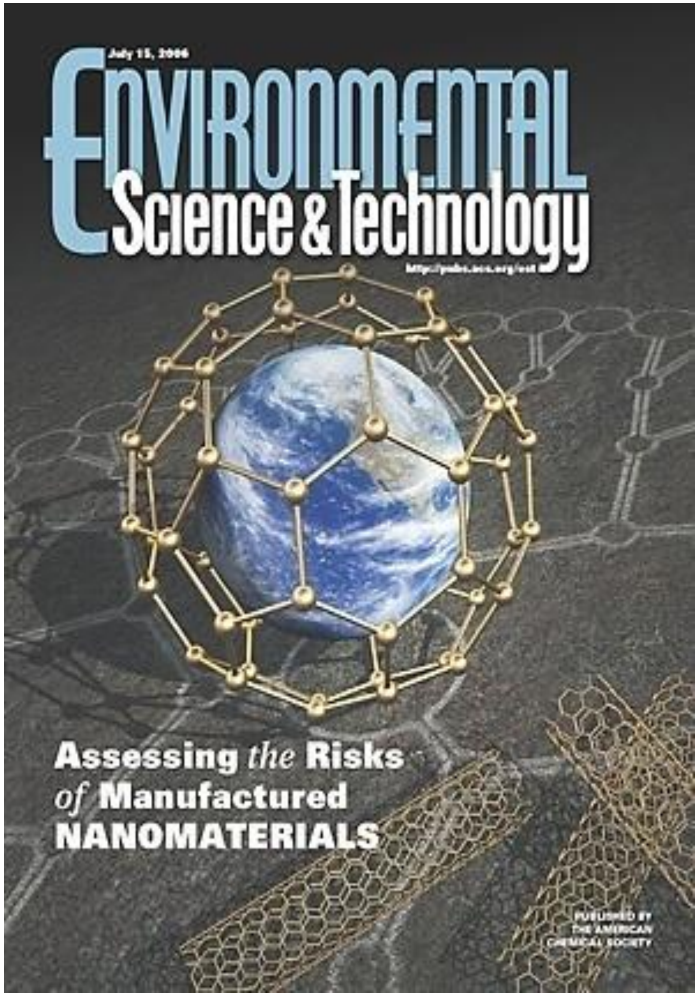
Conceptual Improvements to Water Treatment Through Nanotechnology

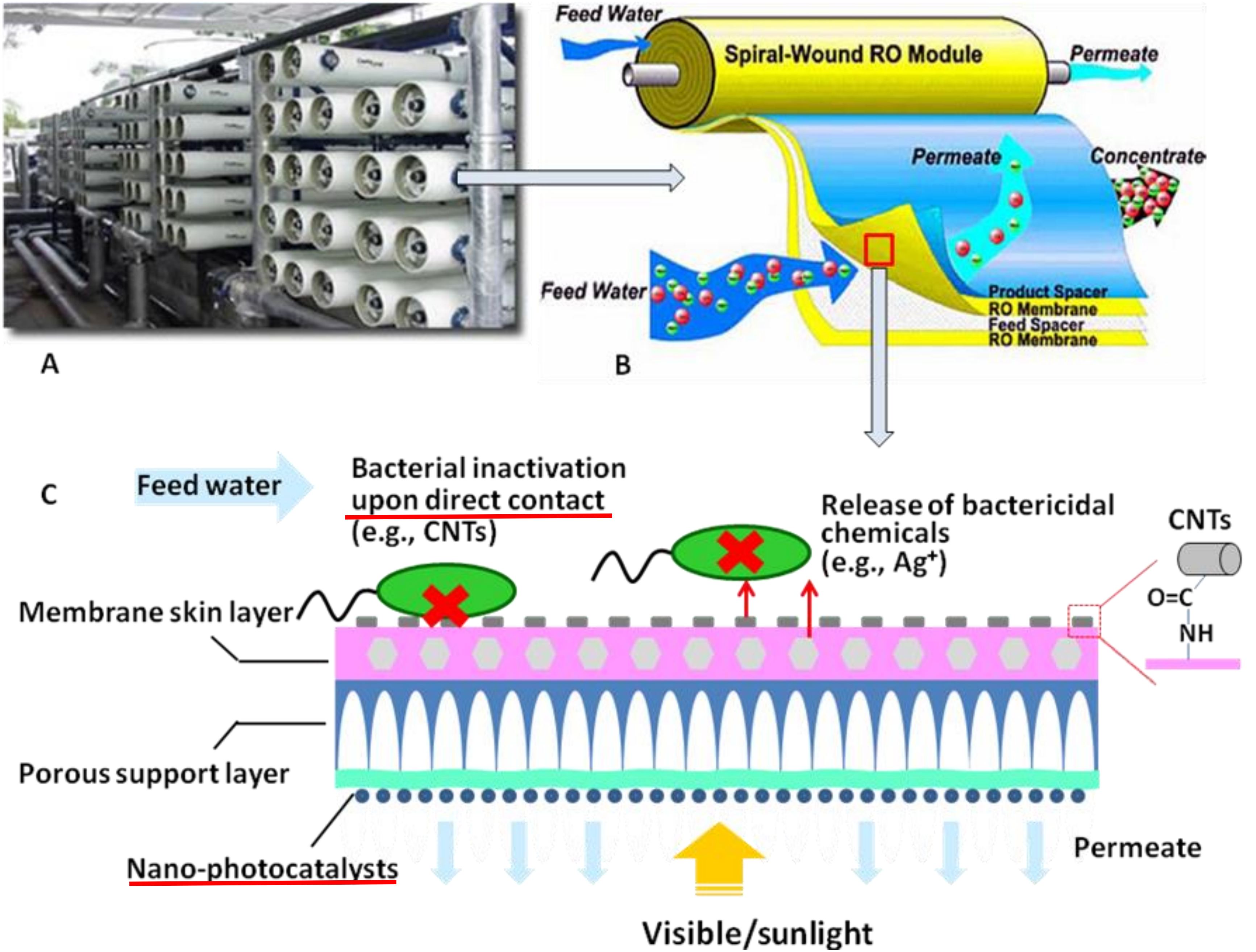


Qu X., J. Brame, Q. Li and P.J.J. Alvarez (2012). Acc. Chem. Res. doi:10.1021/ar300029v

SUMMARY

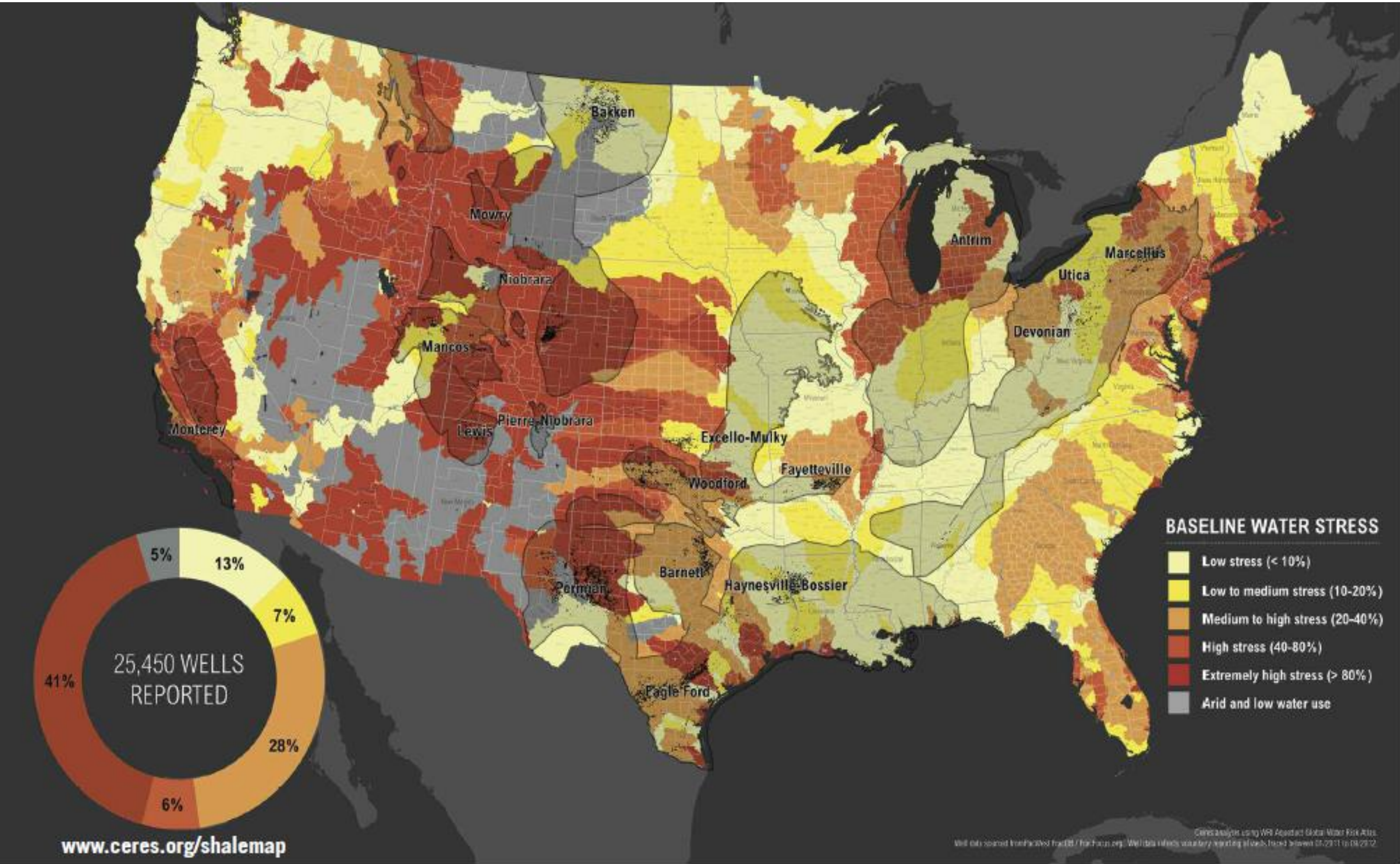
- Antimicrobial NPs can enable microbial control (e.g., DBP-free disinfection, fouling resistant surfaces and membranes, etc.)
- Sub-lethal concentrations of Ni^{2+} and Cd^{2+} hinder biofilm formation by inhibiting quorum sensing at the transcription level.
- Nanotechnology could offer opportunities for controlled released of bactericidal or QS-interrupting metals



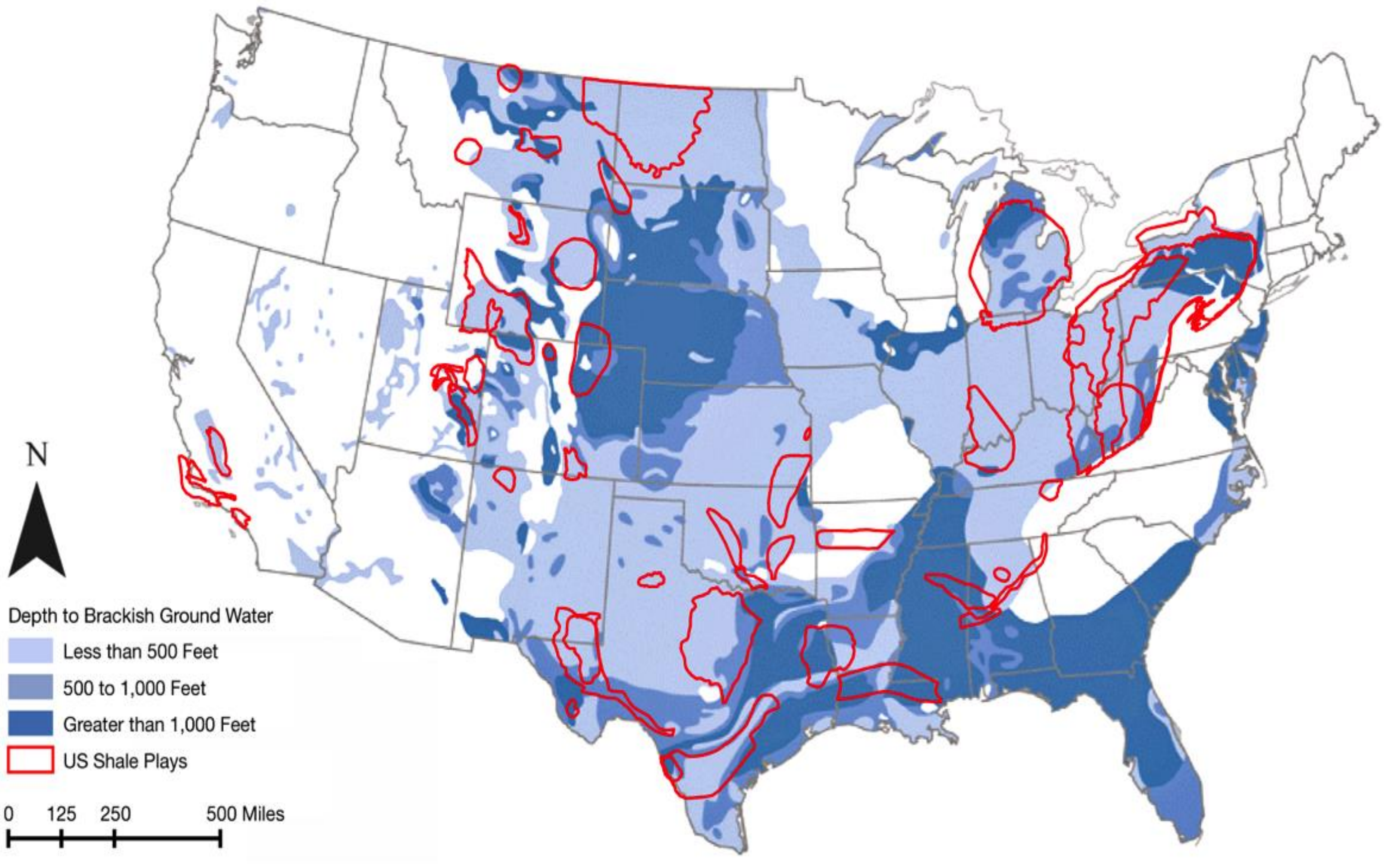


Qu X., J. Brame, Q. Li and P.J.J. Alvarez (2012). *Acc. Chem. Res*. doi:10.1021/ar300029v

Fracking in drought-prone regions represents both a water supply and pollution control challenge



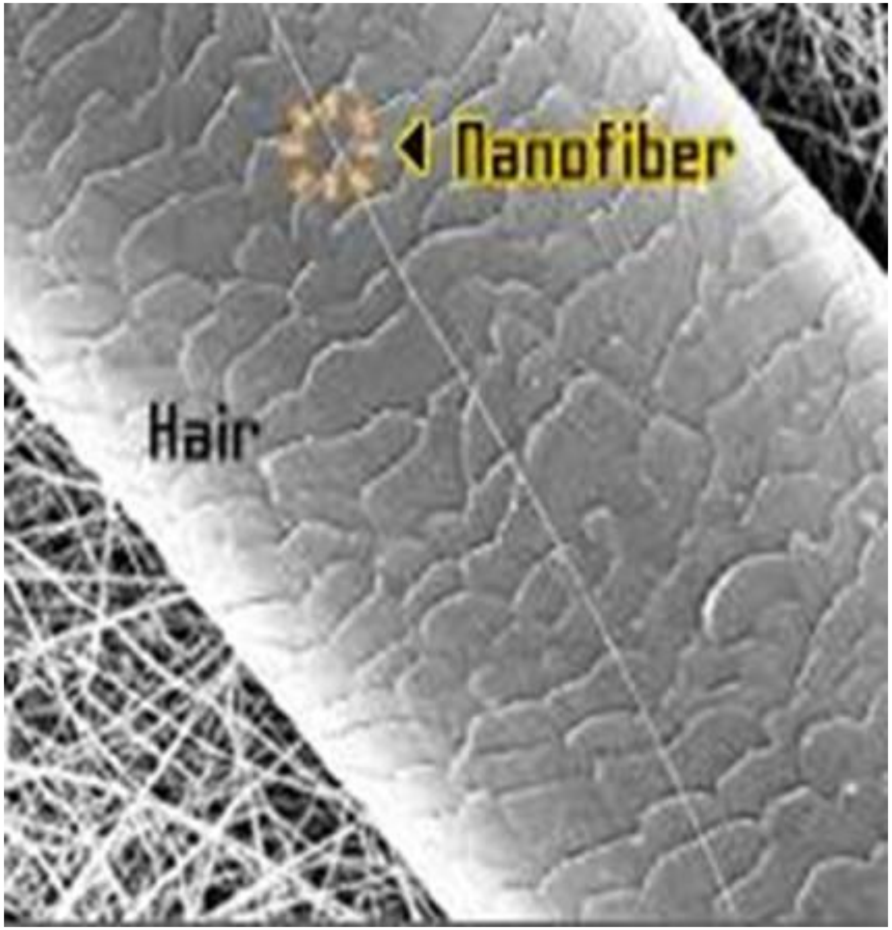
Use Brackish Groundwater for Fracking? (Geospatially consistent)



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."

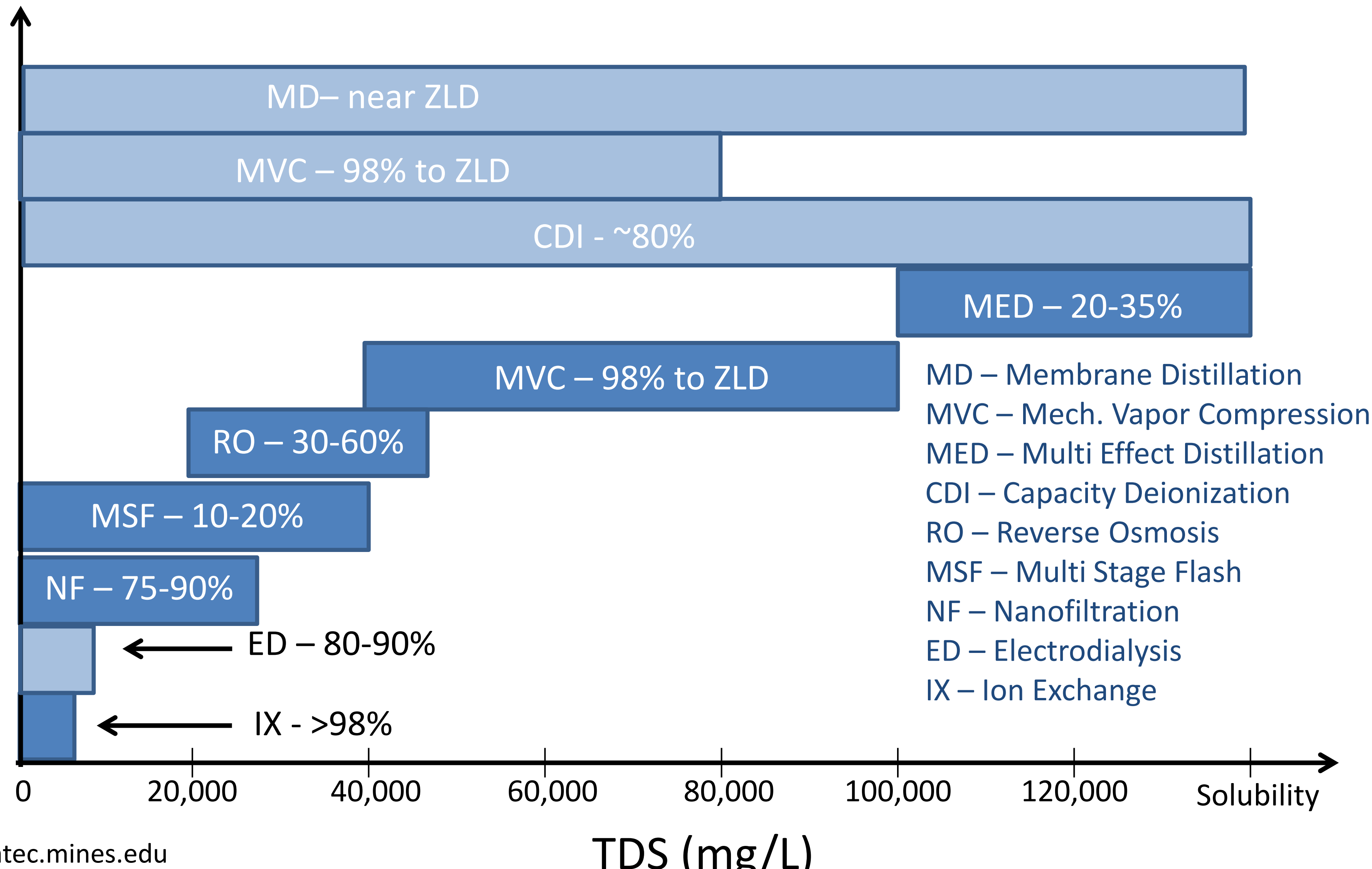
-National Nanotechnology Initiative



1) Need for Low-Energy Desalination

- High TDS represents a beneficial disposition challenge (discharge regulations)
- Multivalent cations (Ca^{2+}, Ba^{2+}, Sr^{2+}, Fe^{2+}/Fe^{3+}) interfere with performance of friction reducing polymers and also form scale (flow assurance)
- Naturally occurring radioactive materials
- Toxic inorganic contaminants (e.g., Zn^{2+})

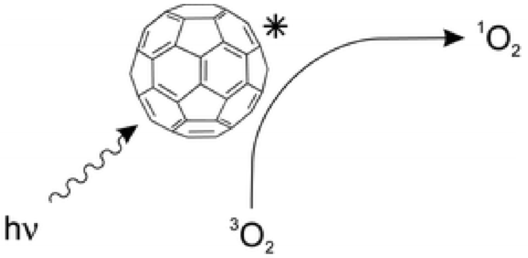
Desalination Technologies: Applicability and Water Recovery



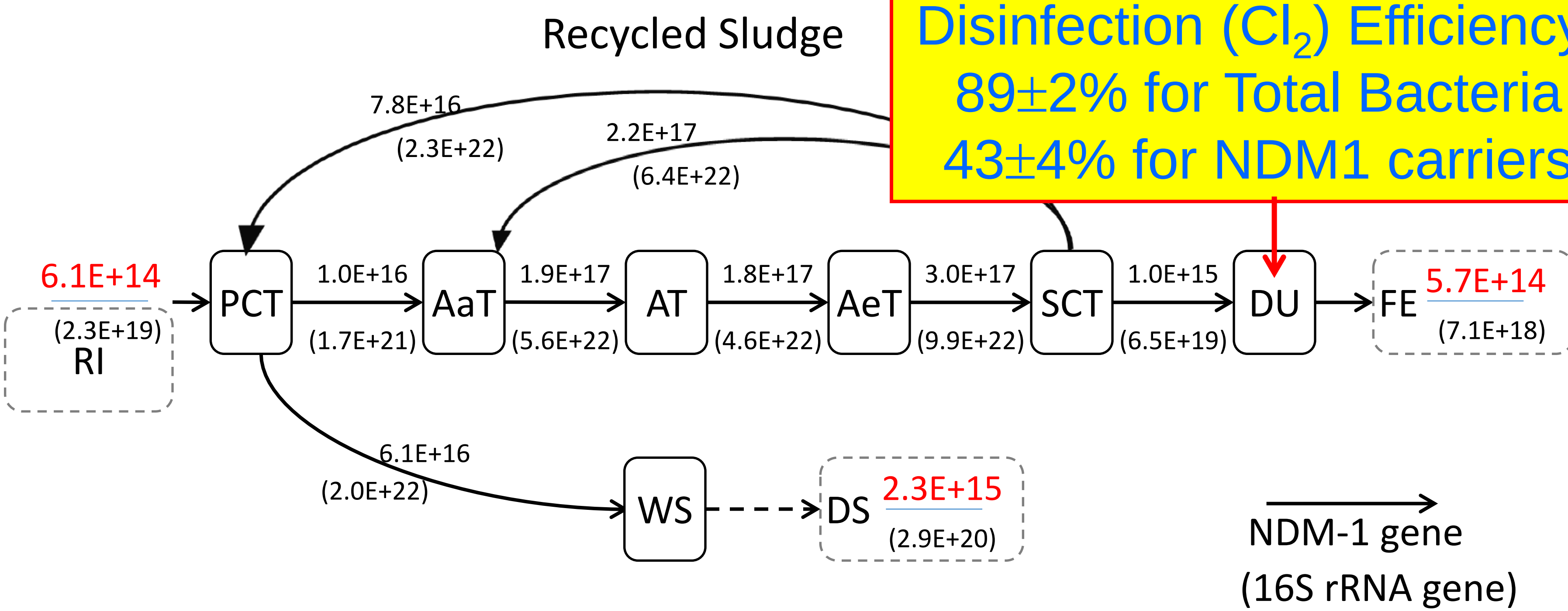
aqwatec.mines.edu

Nano-Enabled Water Treatment @ Rice

- Sand filter coated with nano-magnetite to remove As (pilot in Guanajuato, Mexico, reported by BBC, NY Times, Forbes and CBC).
- Fouling-resistant membranes that also inactivate virus (nAg, nano-TiO_2)
- Pd/Au hypercatalysts to treat TCE (Pilot at Dupont site)
- Novel amino-fullerene photocatalysts to enhance UV and solar disinfection and advanced oxidation processes



Proliferation of Multi-drug Resistant "Superbugs" (NDM-1 positive) from Sewage Treatment Plants

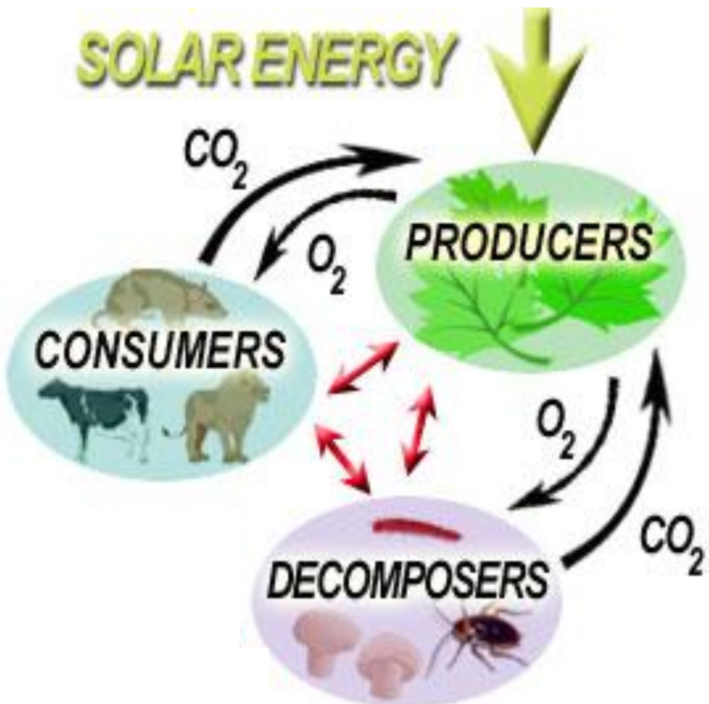


Disinfection (Cl_2) Efficiency:
89±2% for Total Bacteria
43±4% for NDM1 carriers

NDM-1 flow output (genes/day) was
4.6-fold greater than influent values

Yi L., F. Yang, J. Mathieu, D. Mao, W. Qing, and P.J.J Alvarez (2014). ES&T Letters. (1), 26−30

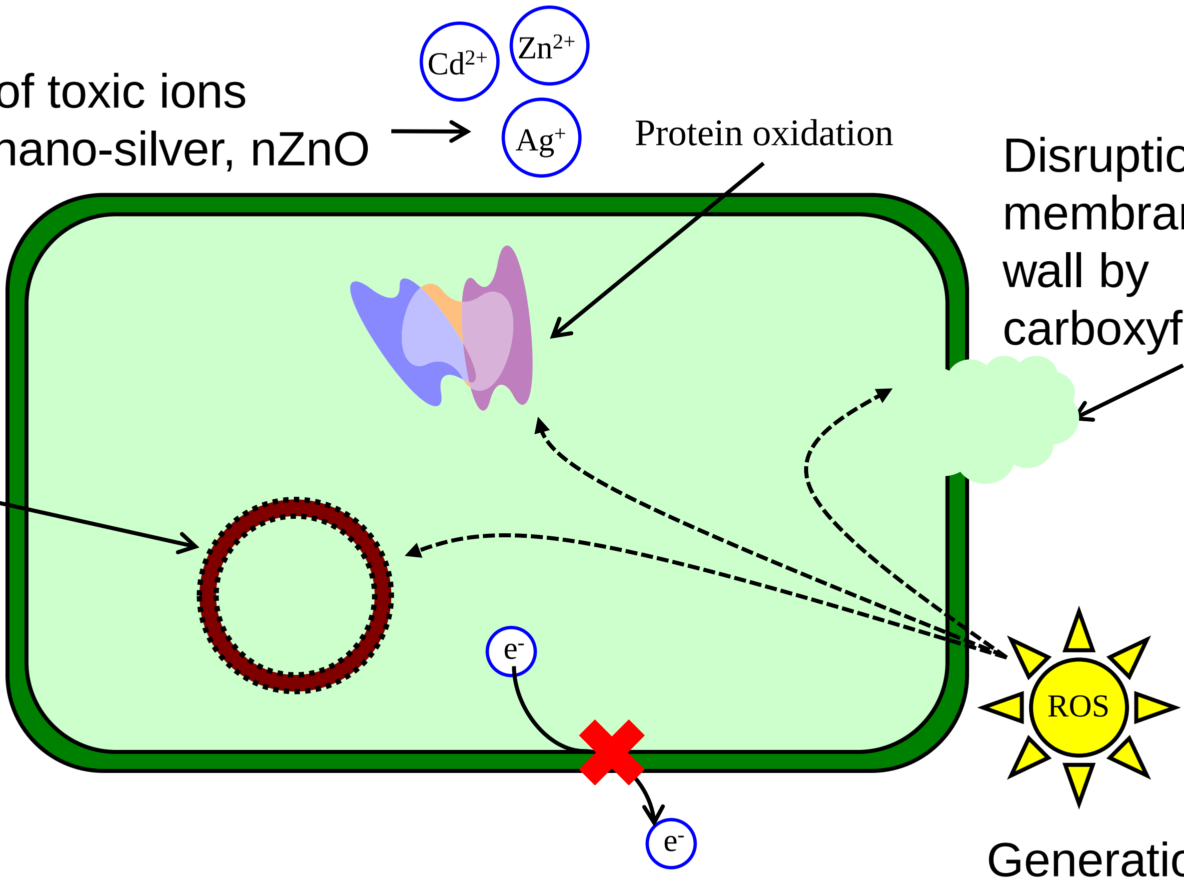
Microbial-nanoparticle Interactions to Inform Risk Assessment



- 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*?)

Selected Antimicrobial Mechanisms

Release of toxic ions
by QDs, nano-silver, nZnO



Disruption of membrane/ cell wall by carboxyfullerene

DNA damage

Interruption of respiration and protein oxidation upon contact (e.g., nC_{60} , CeO_2)

Generation of Reactive Oxygen Species by TiO_2 & aminofullerenes

Vision: Nano-Enabled Water Treatment & Reuse

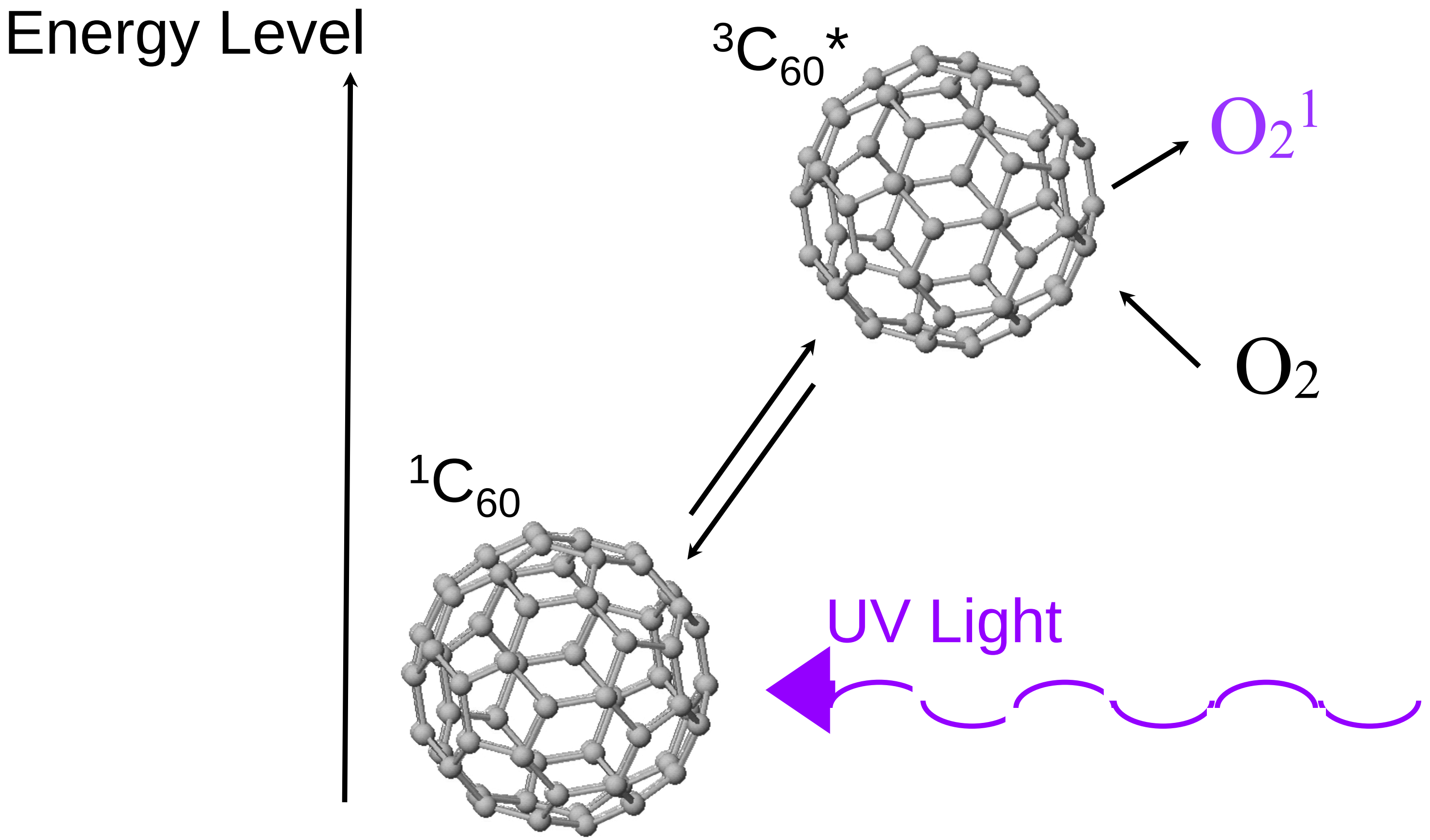
“Nano” particles:

- High surface areas
- Hyper-catalytic functions
- Tunable physical properties
- Multifunctional membranes
- Faster kinetics

Transformative Technologies to

clean water, enhance water infrastructure, & enable integrated water management & reuse

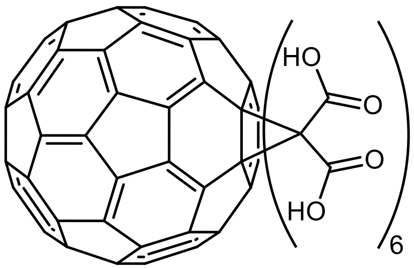
Enable high-performance water treatment and remediation systems with
(1)Less infrastructure,
(2)Less materials/reagents (selective targeting)
(3)Lower costs & energy



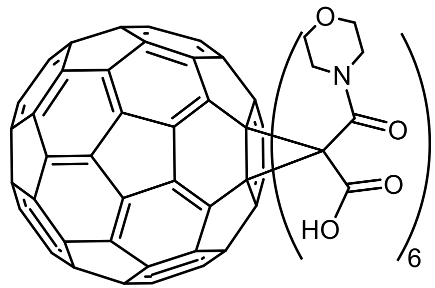
Light excites C_{60} to triplet state. Energy transfer between $^3C_{60}^*$ and molecular oxygen gives rise to singlet oxygen ($^1O_2$)

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

“Water Soluble” Derivatized Fullerenes

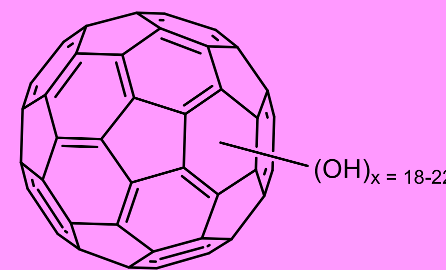


HC1



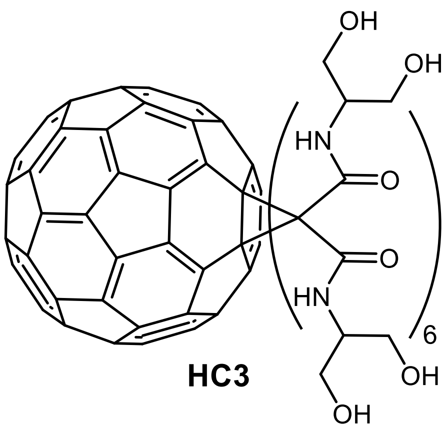
HC2

vs

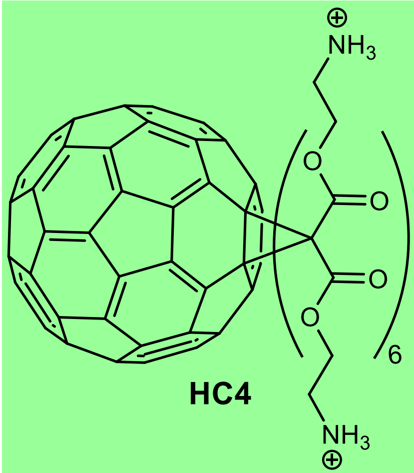


Fullerol

* Commercially Available, MER Corp.



HC3



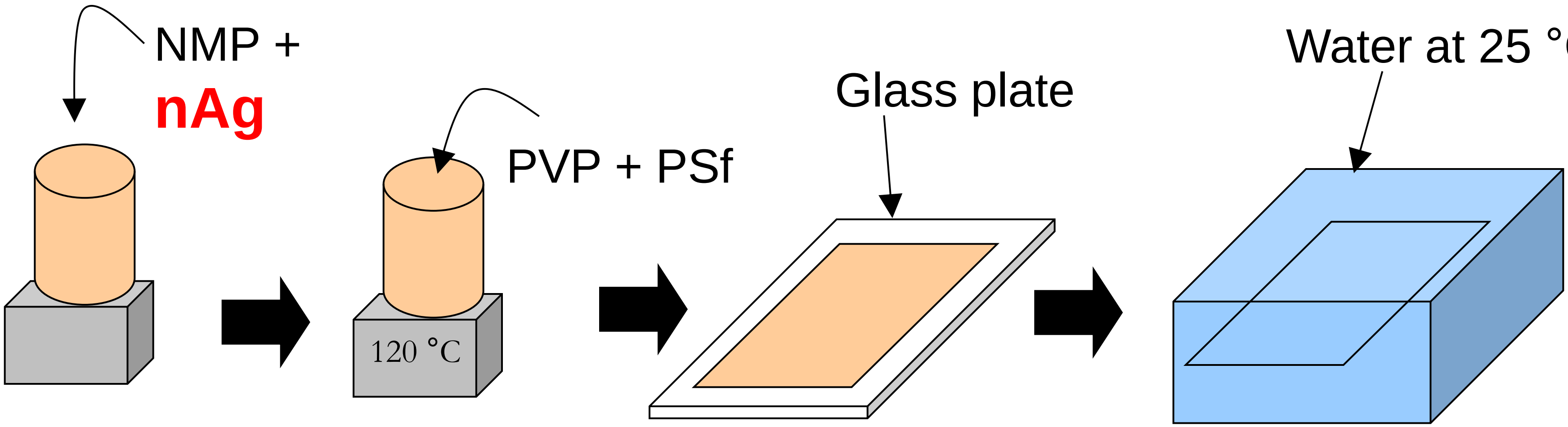
HC4

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

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

Example 2: Biofouling of Water Treatment Membranes

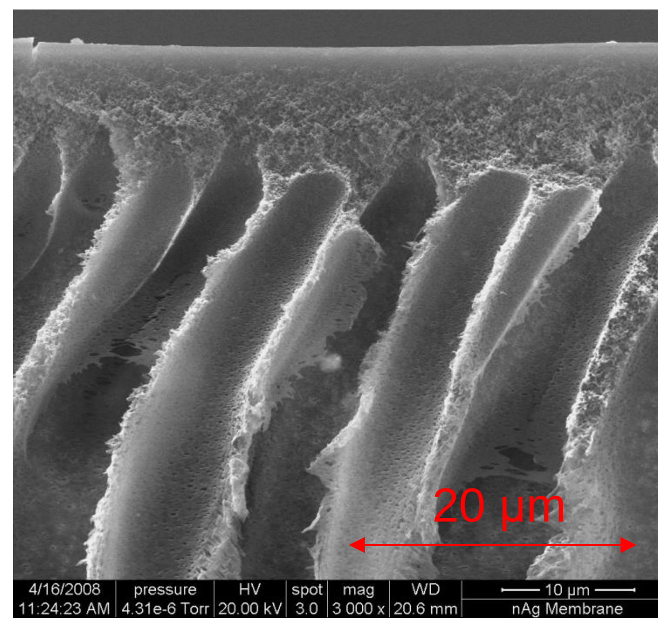
Fouling-Resistant UF Membrane Fabrication (Wet Phase Inversion)



1. Collodion preparation :

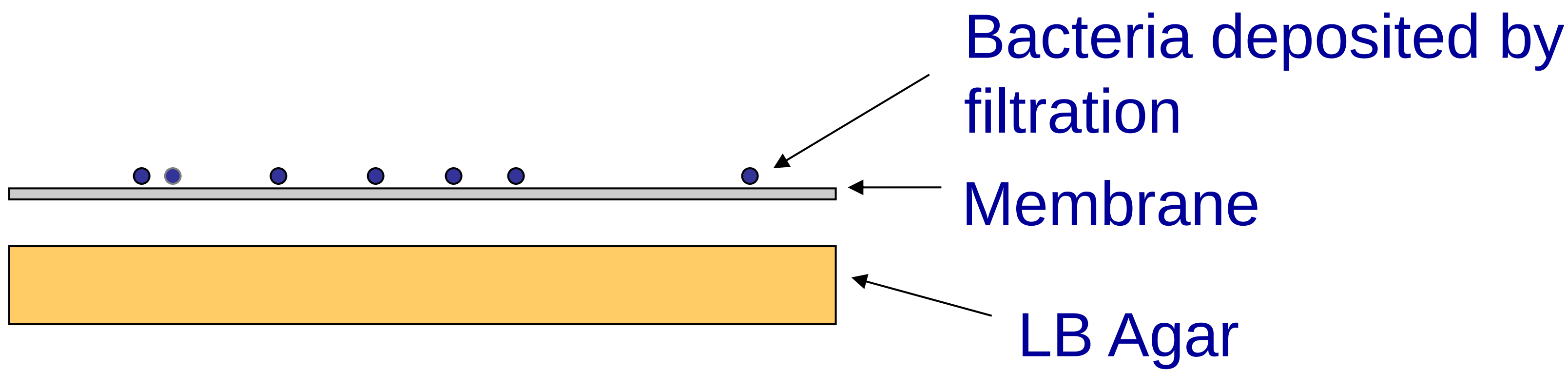
2. Film casting at room temperature

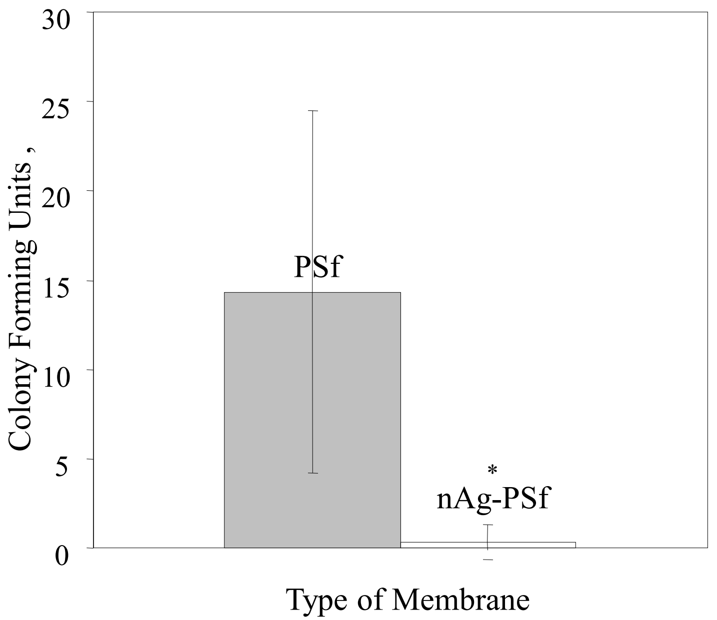
- Nanoparticle solubilisation in NMP. Ultrasonication (100 W, 4 min)
- Addition of PVP at 70 °C
- Slow addition of PSF while stirring at 120 °C



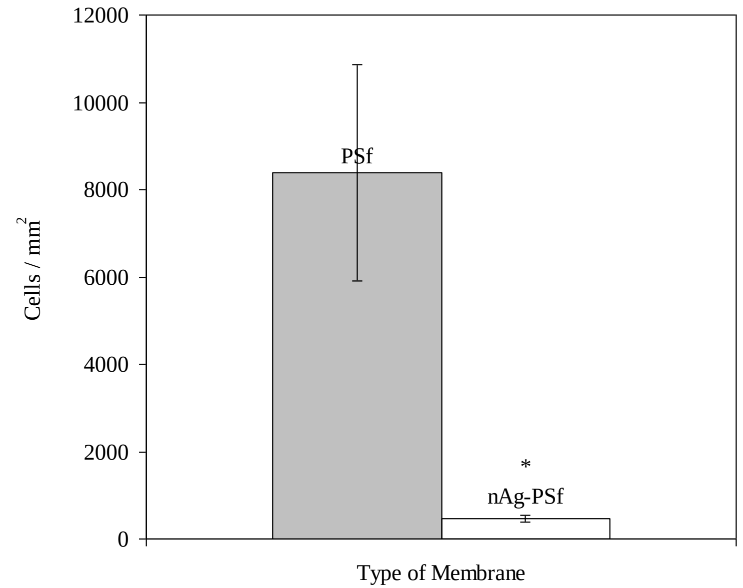
NMP = N-methylpyrrolidone ; PSf = Polysulfone ; PVP=Poly(vinylpyrrolidone)

Bacterial growth inhibition test





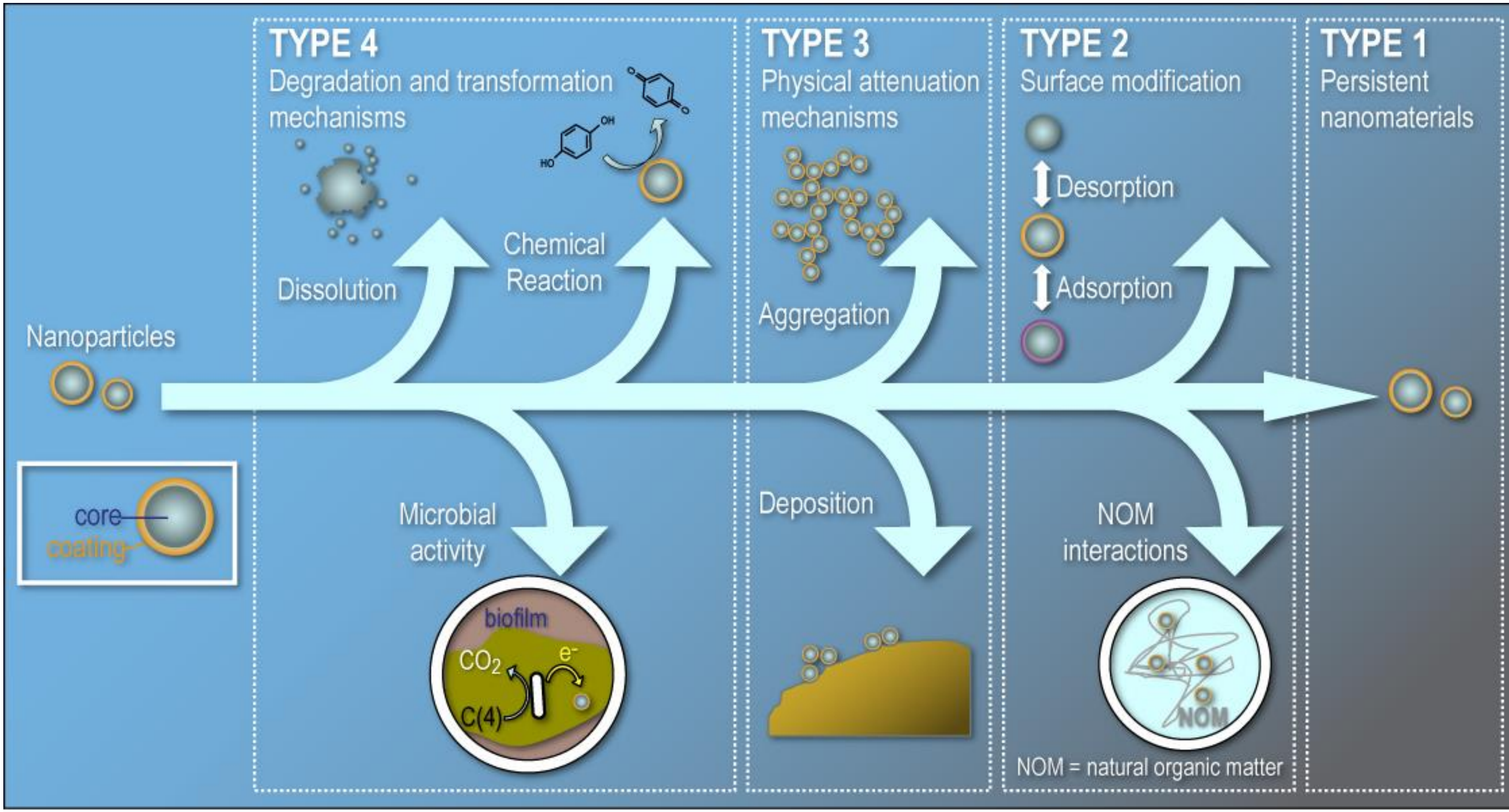
Inhibition of growth of *E. coli*



Inhibition of *E. coli* attachment onto membrane surface

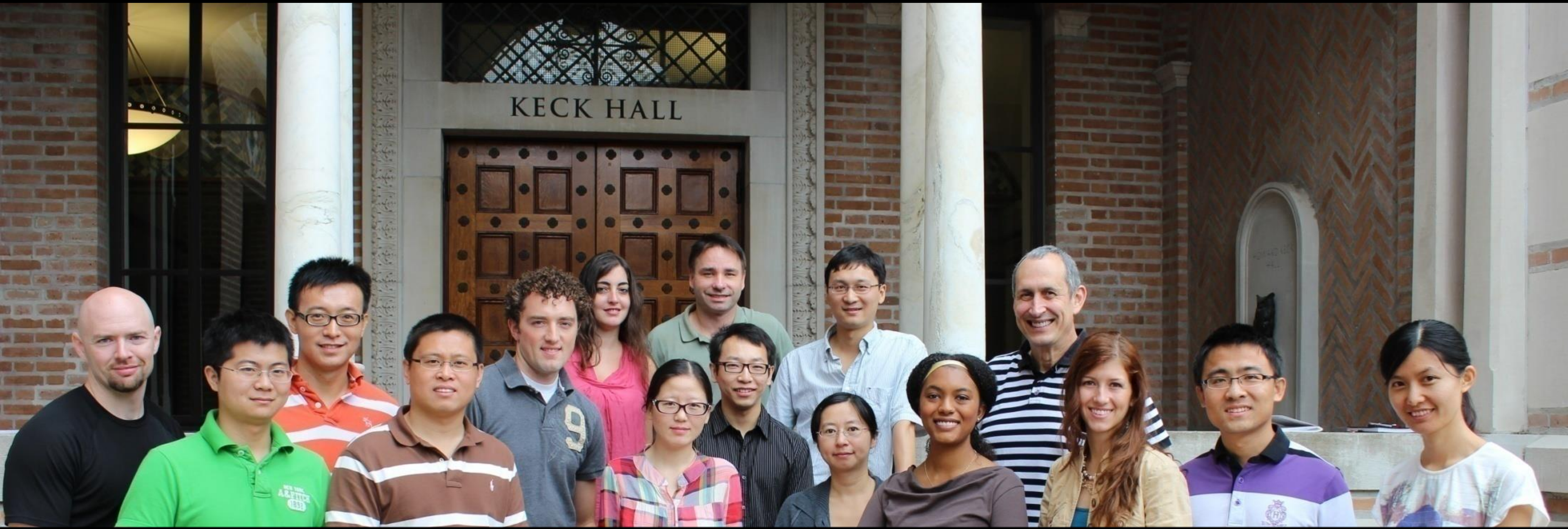
Zodrow K., L. Brunet, S. Mahendra, Q. Li, and P.J.J. Alvarez (2009). *Wat. Res* doi:10.1016/j.watres.2008.11.014

Nanoparticle Modifications in the Environment



Alvarez P.J.J., V. Colvin, J. Lead and V. Stone (2009). Research Priorities to Advance Eco-Responsible Nanotechnology. ACS Nano 3(7): 1616-1619.

Thanks! - Graduate Students and Postdocs
NSF, EPA, CBEN, FAO, NERC, BP

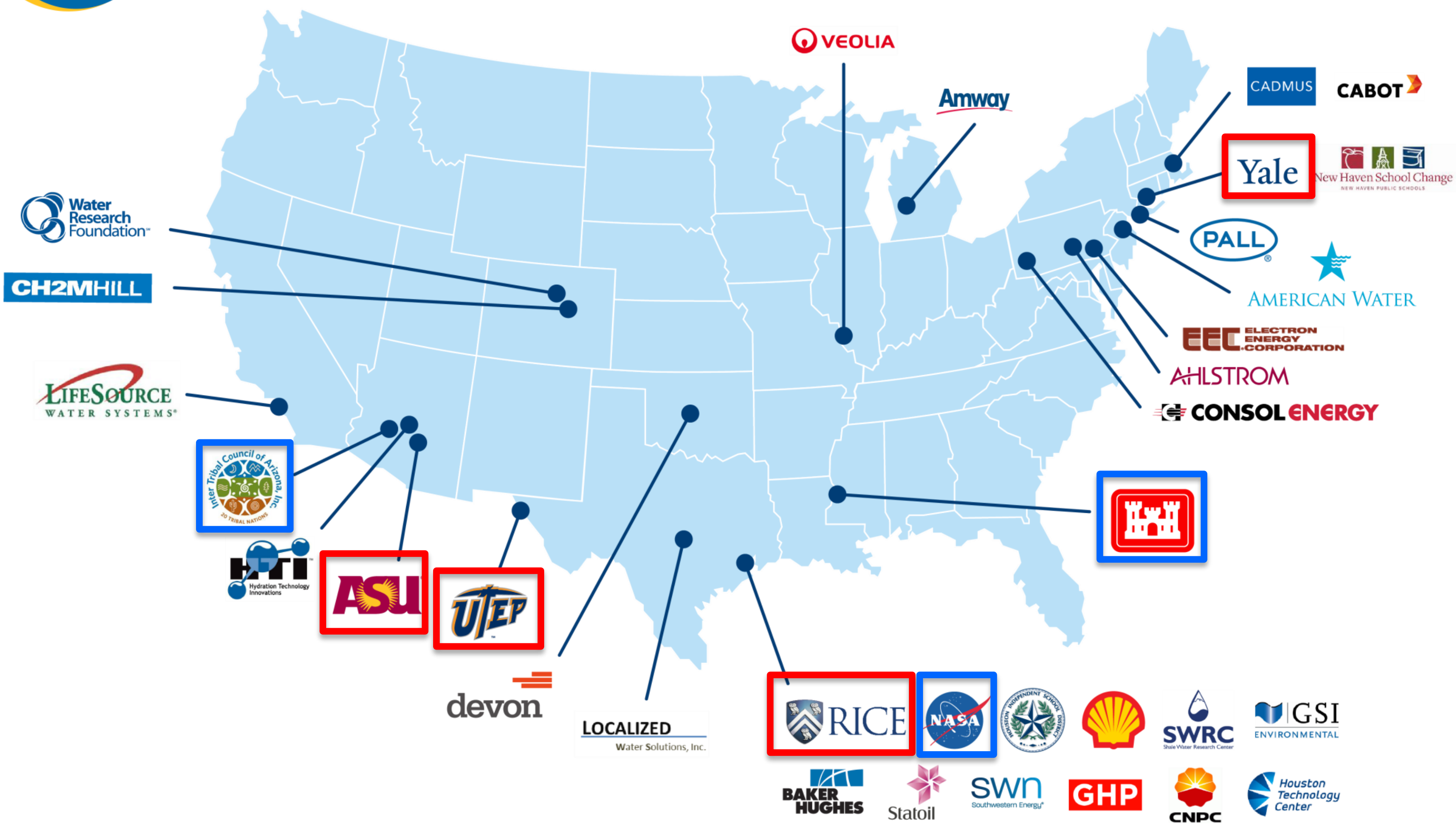


Ph.D. M. Vermace; Craig Hunt; Marcio da Silva; Nanh Lovanh; Alethia Vazquez; Roopa Kamath; Michal Rysz; Natalie Capiro; Delina Lyon; Rosa Dominguez, Dong Li; Diego Gomez, Jacques Mathieu, Leti Vega, Xiaolei Qu, **Jon Brame,** Jiawei Ma, Pingeng Yu, Mengyan Li, Jing Wang, Ana McPhail, O. Monzon

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 Gottbrath; Matt Wildman; Chad Laucamp; Todd Dejournet; Sascha Richter; Nanh Lovanh; 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**; 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**

Some of Our NEWT Partners

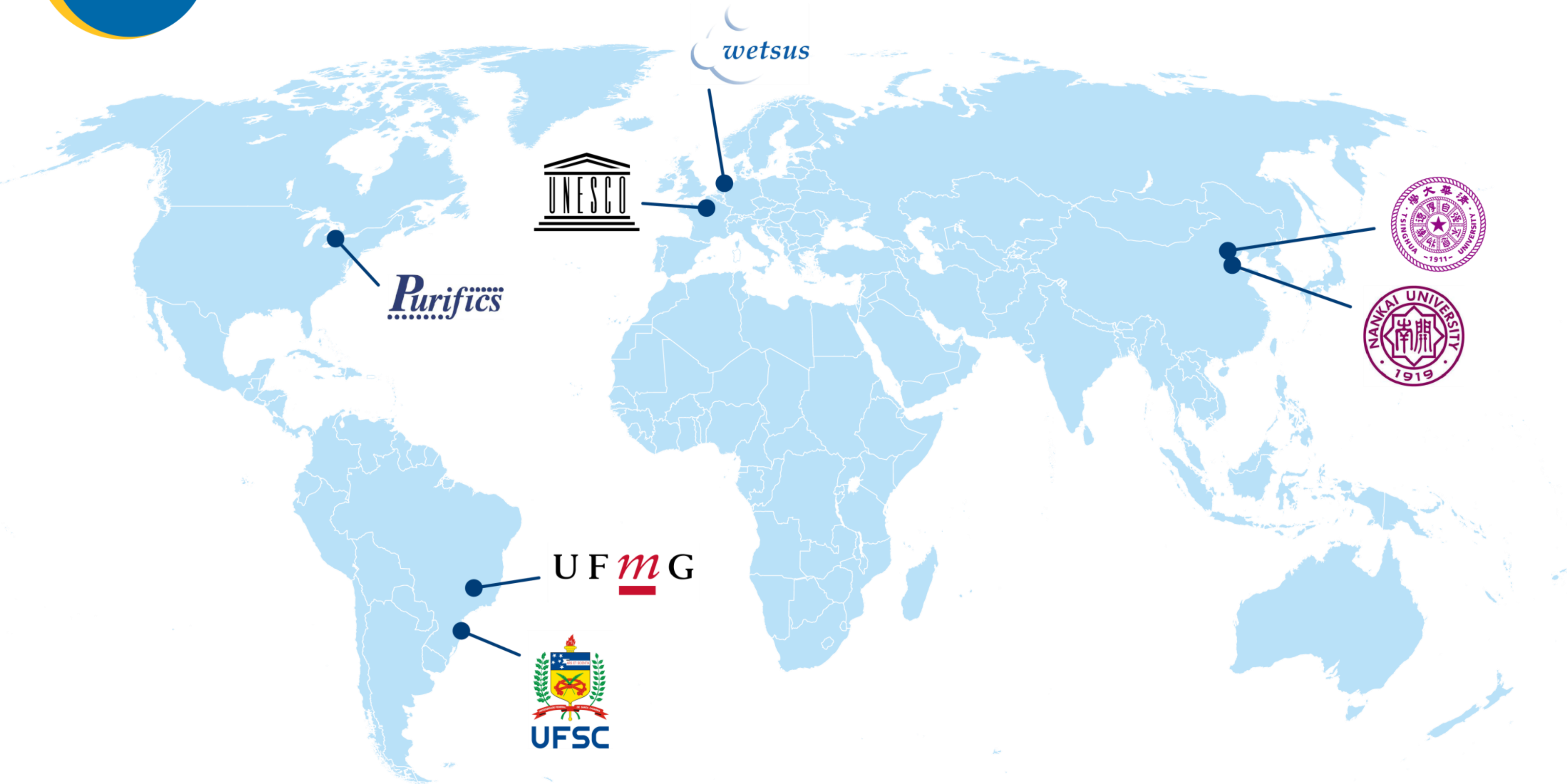


- Innovation across value chain (nanomaterial and equipment manufacturers, service providers, R&D and deployment partners, and users)

NEWT is Supported by Experienced Partners Across the Value Chain

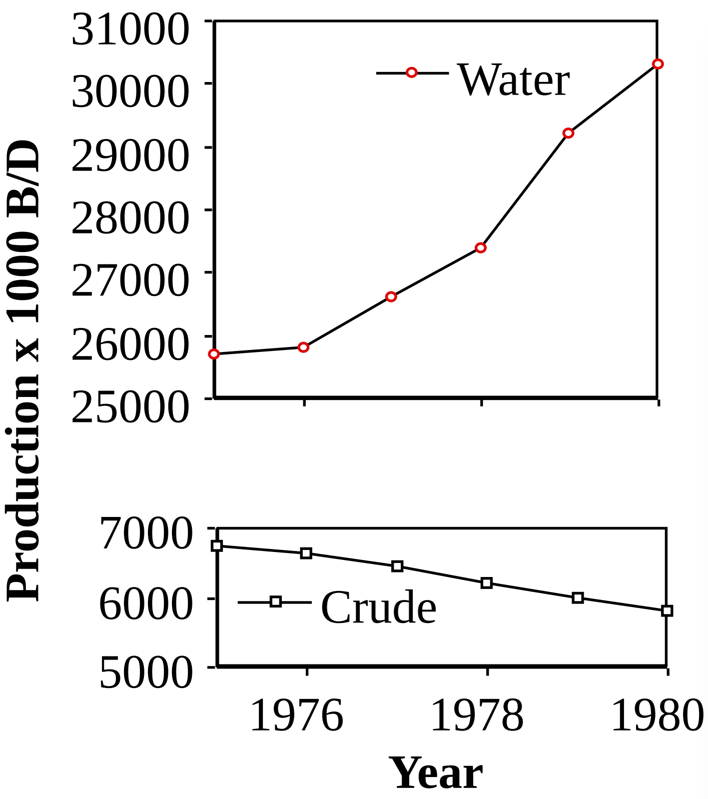
Nanomaterial and advanced material manufacturers	EEC Electron Energy Corporation, CABOT, HTI Hydration Technology Innovations, Purifics
Equipment manufacturers	AHLSTROM, Amway, LifeSource Water Systems, PALL
Research, development and deployment partners	NASA, NSF, CADMUS, GHP, Houston Technology Center, UNESCO, Water Research Foundation, wetsus
Service providers	American Water, Baker Hughes, CH2MHILL, GSI Environmental, Localized Water Solutions, Inc., SWRC Shale Water Research Center, VEOLIA
End users	CNPC, CONSOL ENERGY, devon, SWN Southwestern Energy, Statoil, Inter Tribal Council of Arizona, Inc. 20 Tribal Nations

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

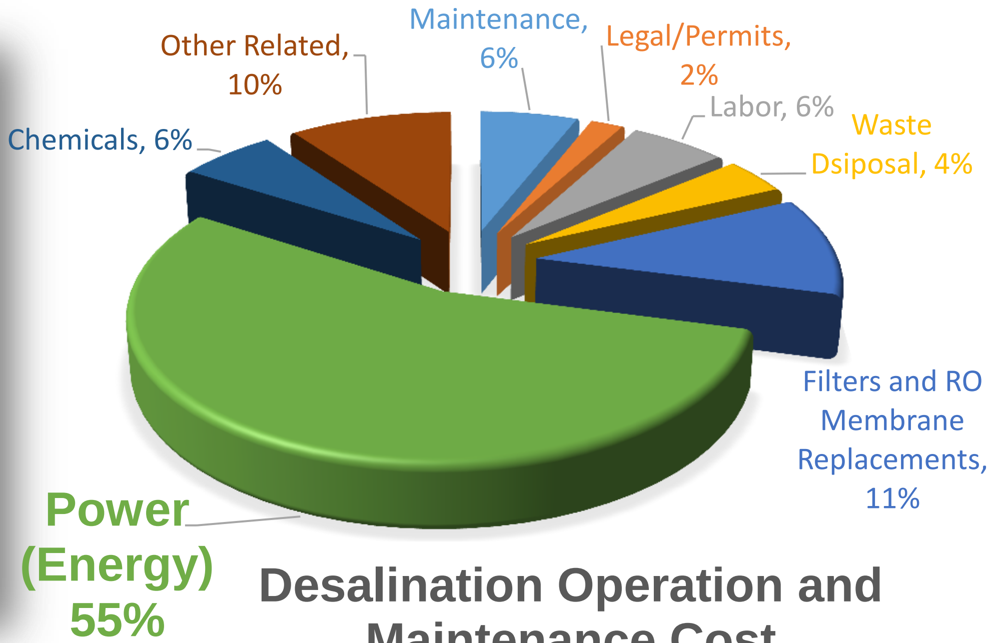
Importance of Water for Energy Production



Water is by far the largest byproduct of the fossil fuel industry
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

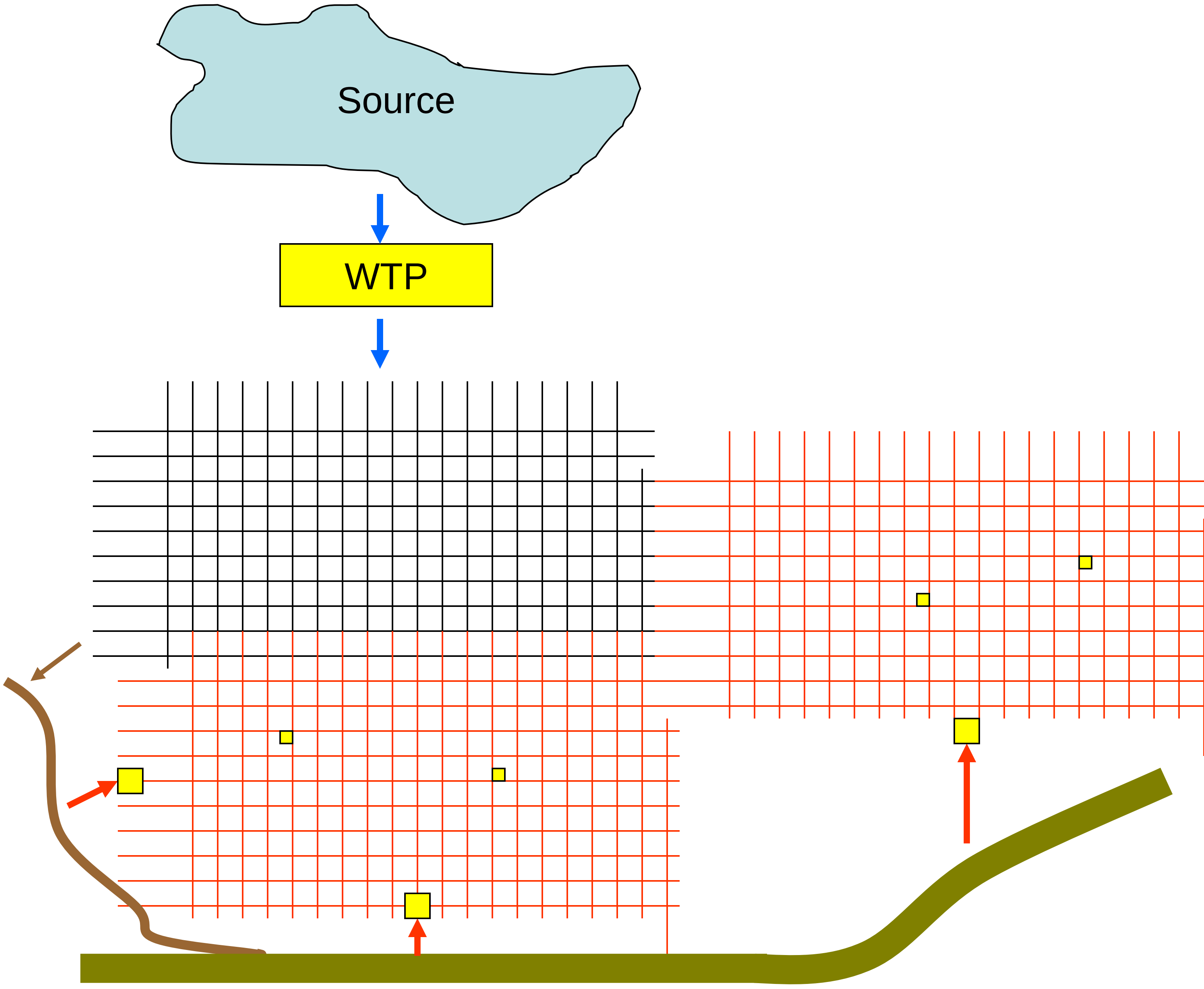


Desalination Operation and Maintenance Cost

20% of 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

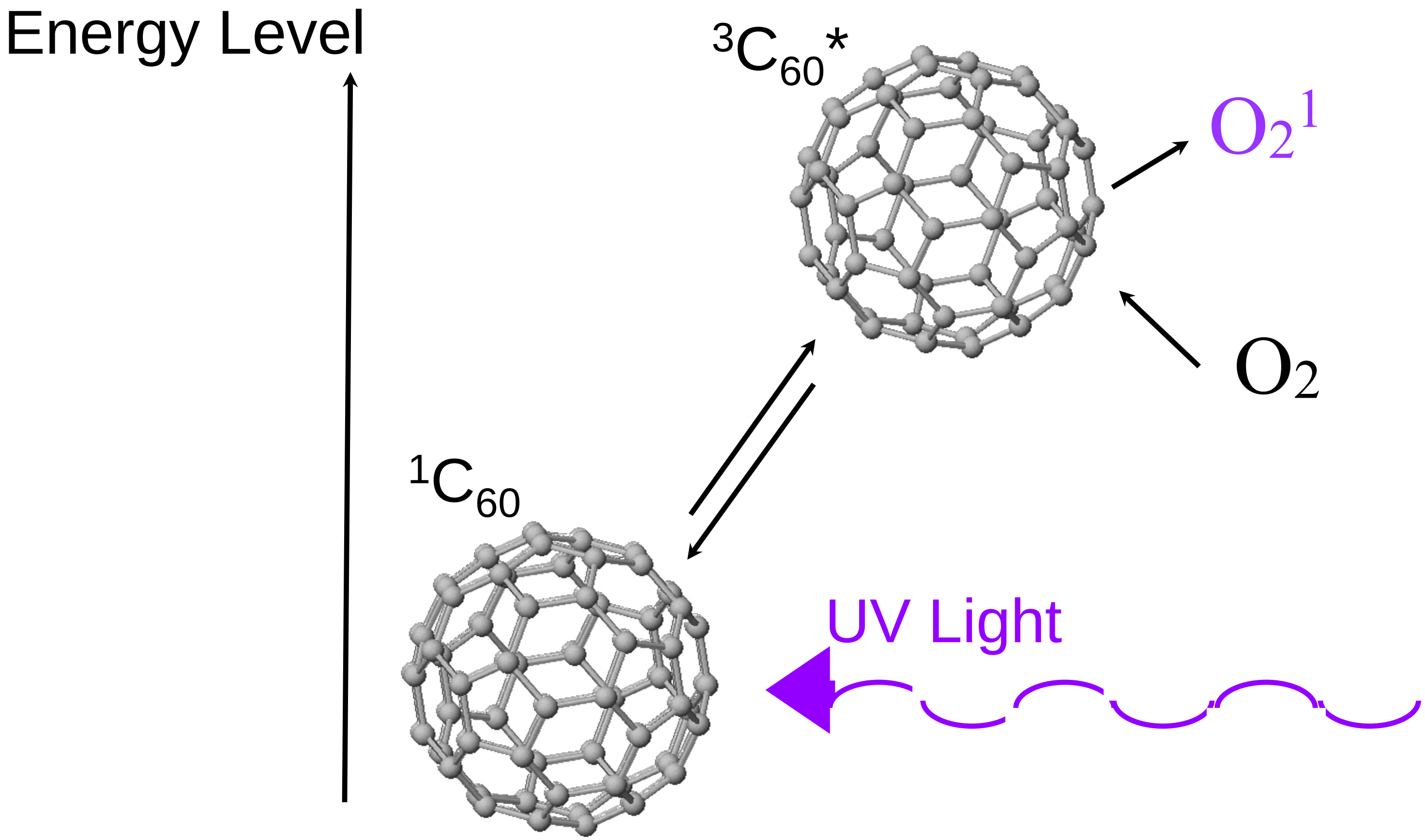

Source
WTP

Drivers for Decentralized (Distributed) 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.
- Reduce energy requirements

Research Needs and Opportunities

- **Network topology analysis to exploit the interconnectivity of complex water systems** (e.g., integrated drinking water, wastewater & storm water networks to enhance water availability and reuse).
- **Advanced materials and technologies** to obtain drinking water from unconventional sources, and to enable reuse and resource recovery (e.g., drinking water, energy, nutrients) from challenging wastewaters.



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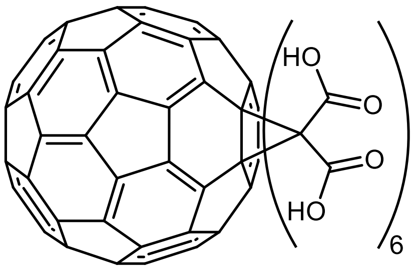
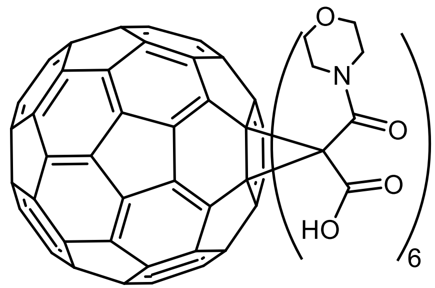
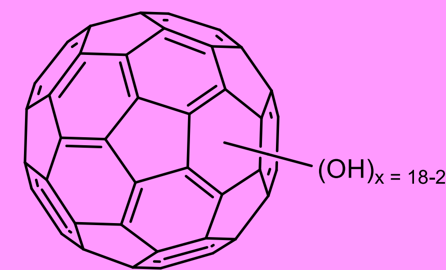


HC1



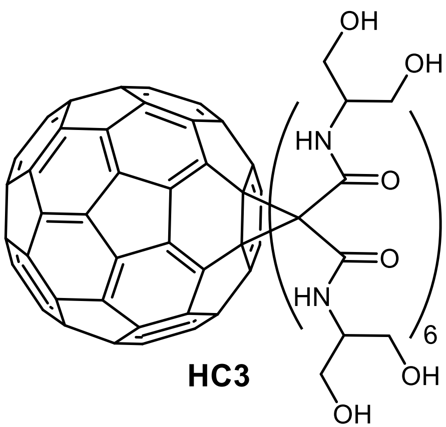
HC2

vs

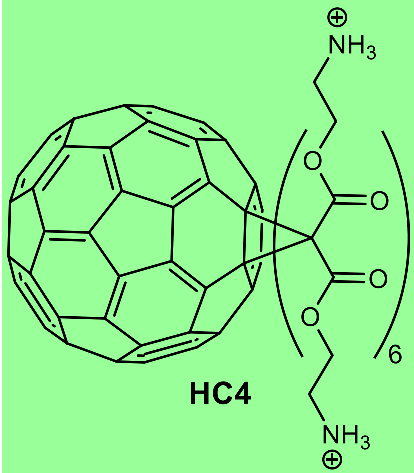


Fullerol

* Commercially Available, MER Corp.



HC3

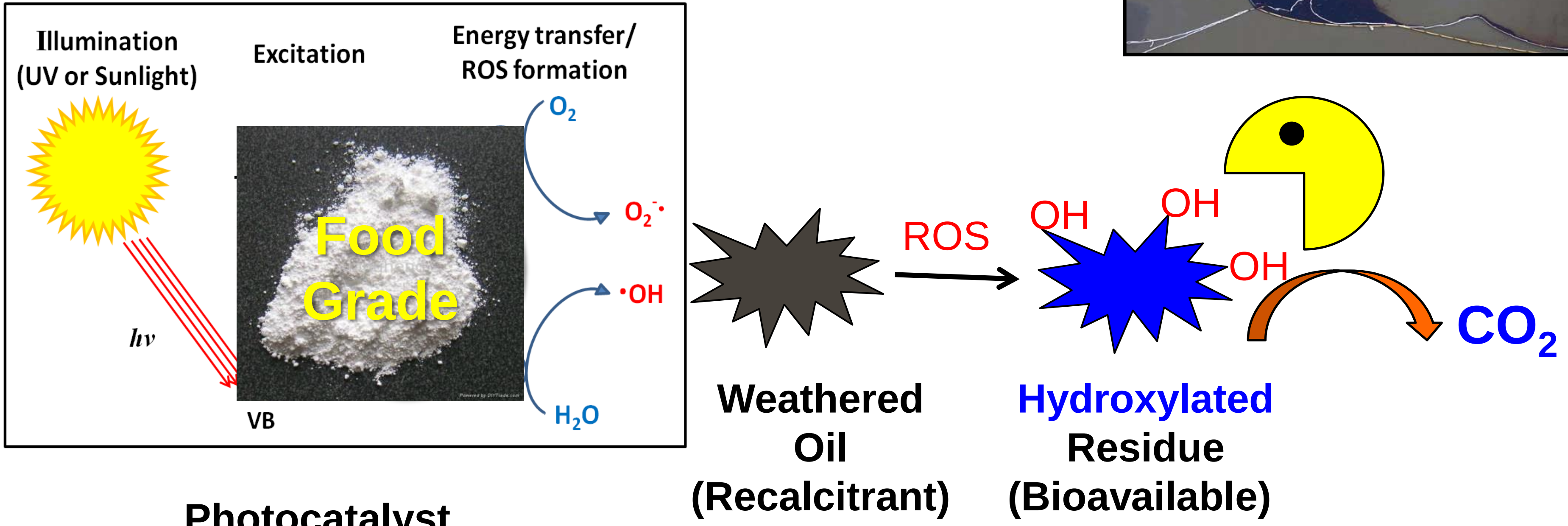


HC4

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

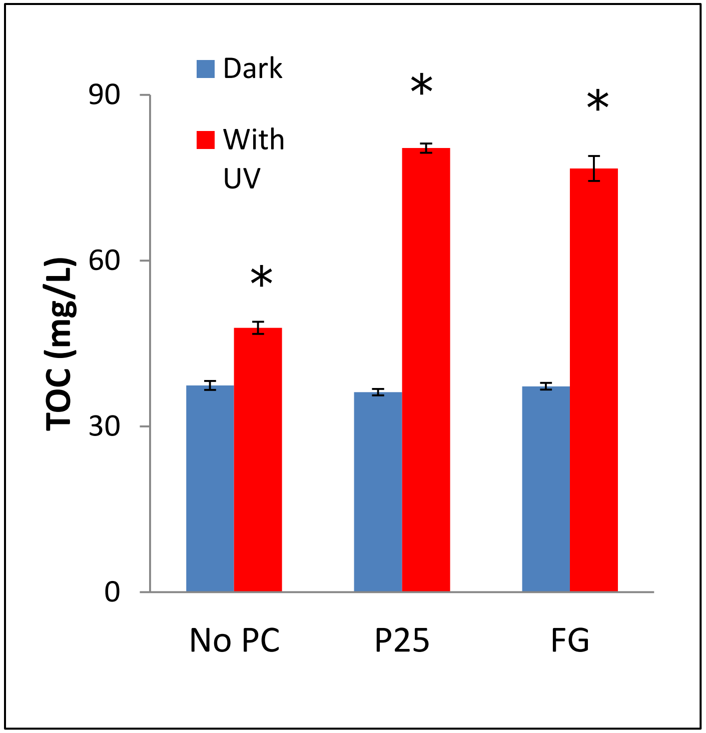
Superior $^1O_2$ Production confirmed by EPR & Laser Flash Photolysis

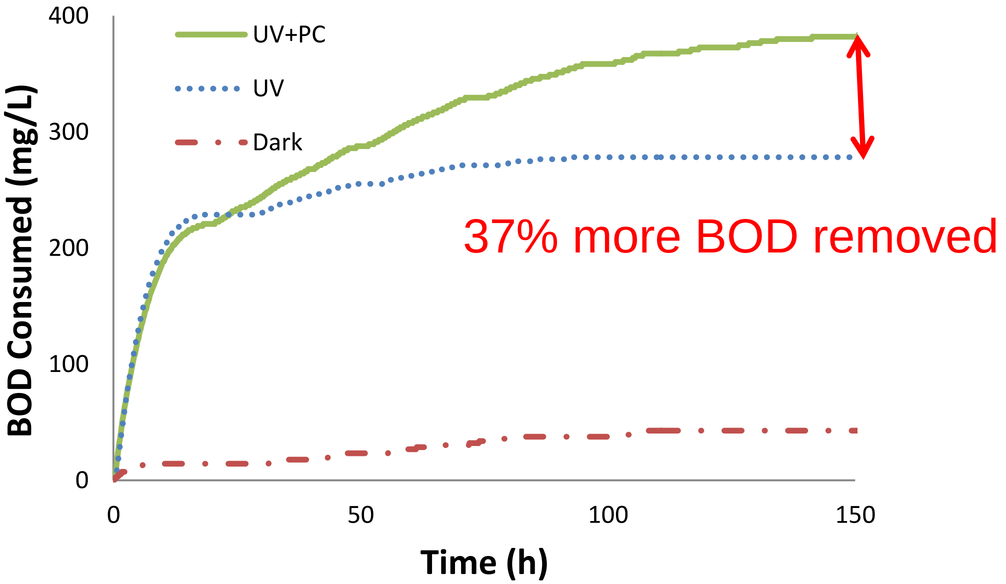
Photocatalytic Hydroxylation of Weathered Oil to Enhance Bioavailability and Bioremediation



Photocatalyst

Photocatalysis Increased Solubilization and Biodegradation of Weathered Oil

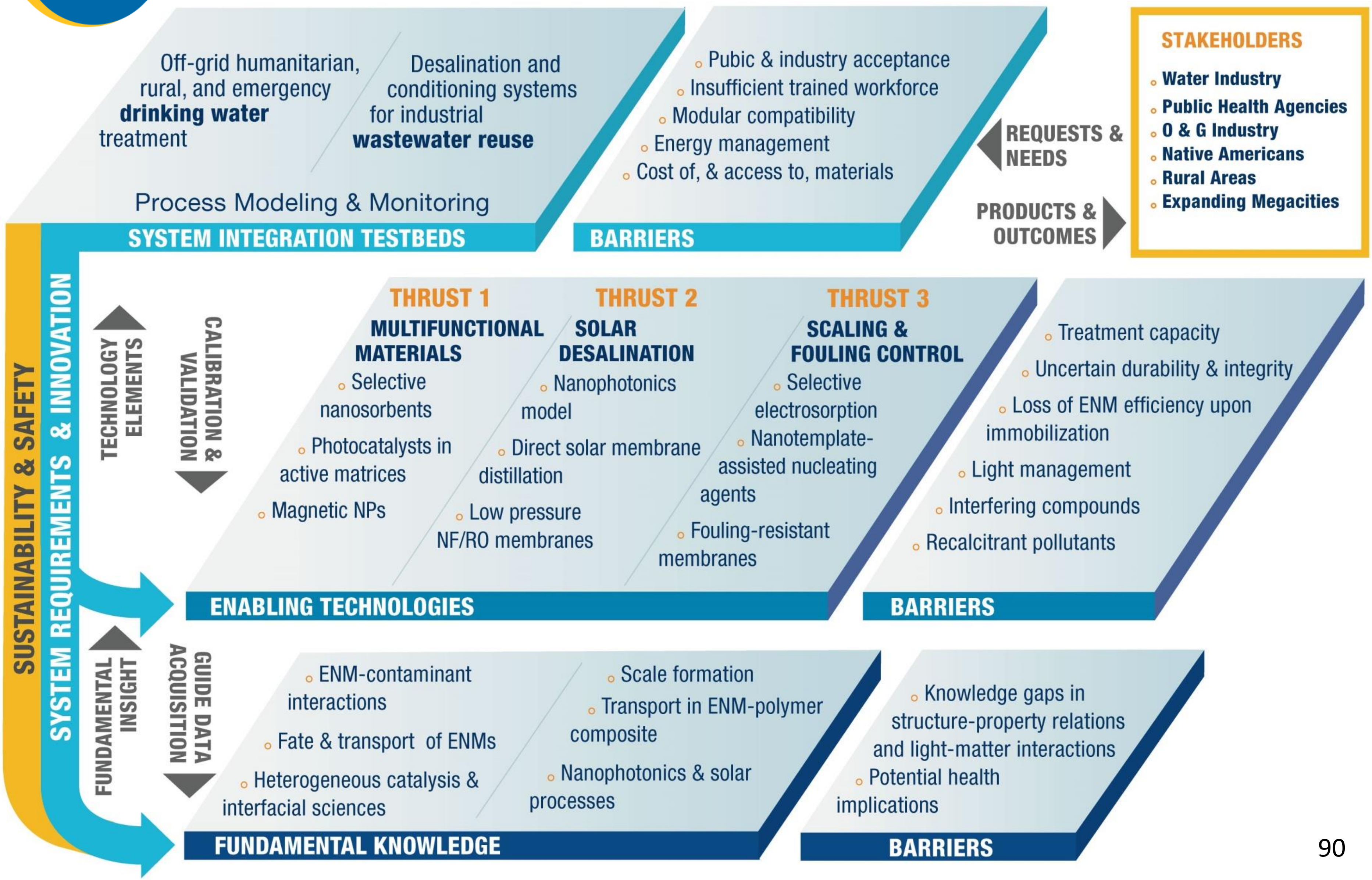




* statistically significant ($p < 0.05$)
after 1-day exposure

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

Top-Down Strategic Plan



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

7 Grand Challenges Related to Water

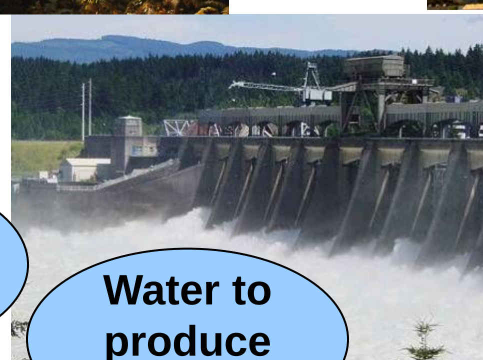
Safe water quality for a growing population

Water infrastructure (distribution & collection)

Distribution between humans and ecosystems

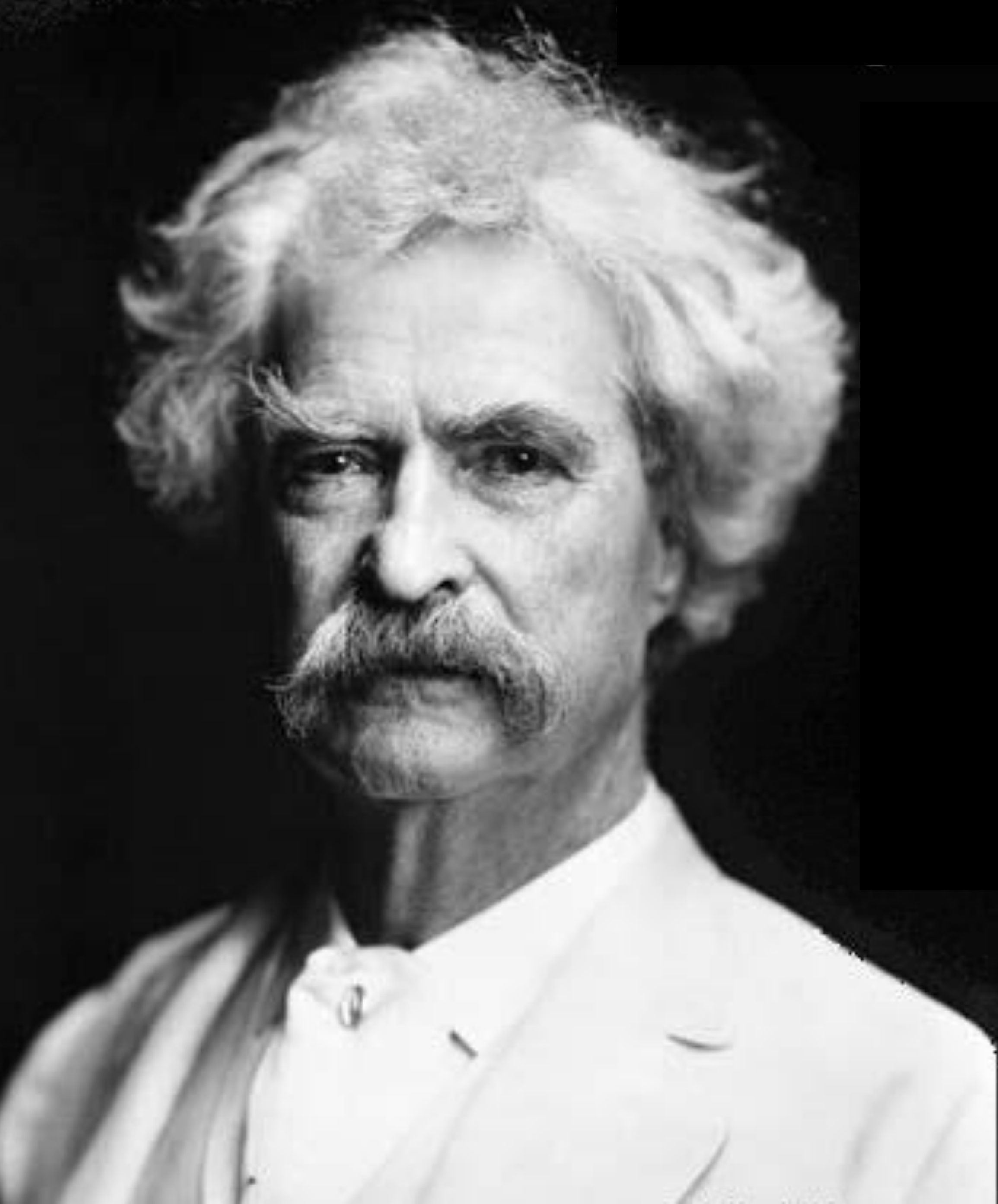
Water induced disasters and flood protection

Enough food for all



Water to produce energy

Solution for water conflicts and fair water share for all



"Whiskey is for Drinking;

Water is for Fighting Over"

~Mark Twain