



Since 1959

Water, Droplets and Ice

Examples of Science for Sustainability

Thalappil Pradeep

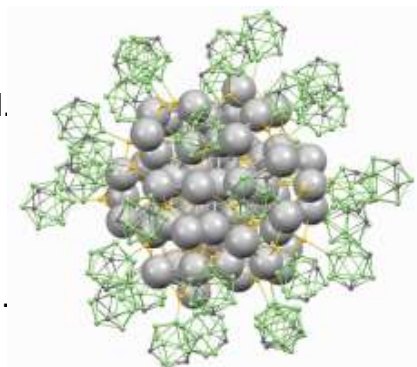
Institute Professor, IIT Madras

pradeep@iitm.ac.in

<https://pradeepresearch.org>

Co-founder

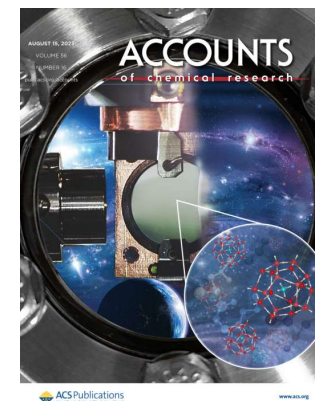
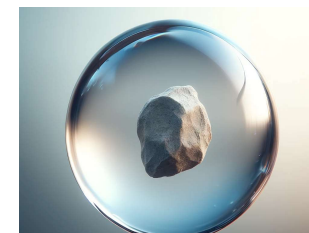
InnoNano Research Pvt. Ltd.
InnoDI Water Technologies Pvt. Ltd.
VayuJAL Technologies Pvt. Ltd.
Aqueasy Innovations Pvt. Ltd.
Hydromaterials Pvt. Ltd.
EyeNetAqua Solutions Pvt. Ltd.
DeepSpectrum Innovations Pvt. Ltd.



Professor-in-charge



International Centre for Clean Water



Associate Editor

3rd International Conference on Energy, Functional
Molecules/Materials and Nanotechnology, Kumaun University
Nainital, Uttarakhand, March 20-22, 2025





“Pale blue dot” Voyager 1 Feb. 14, 1990

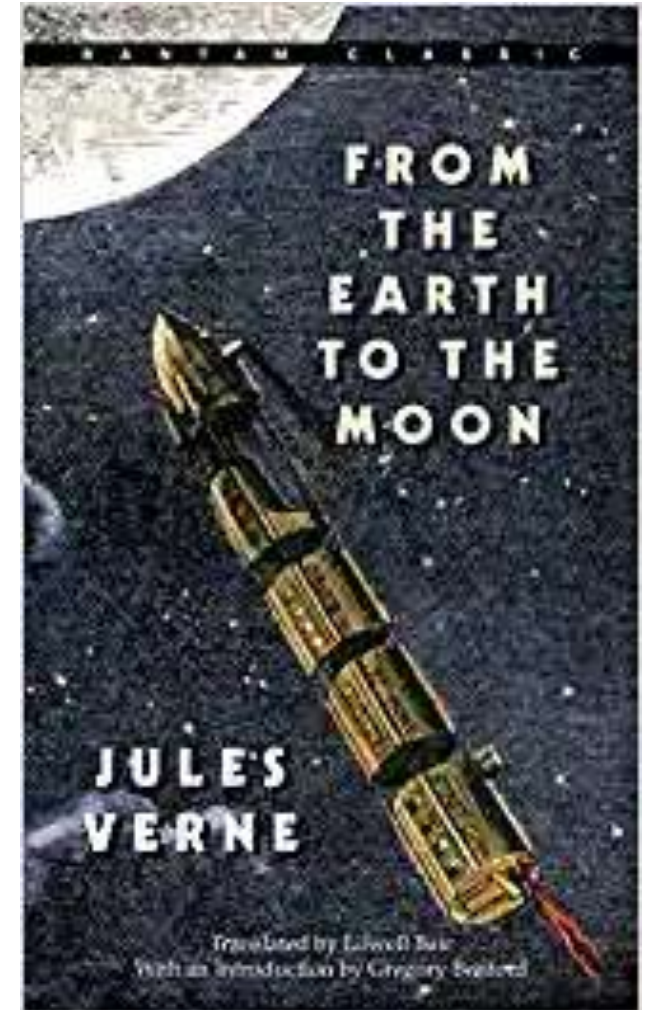
Water is the most important inheritance of our planet



From S. Vishwanath

© Robert Szucs/Grasshopper Geography

Our dreams become reality
with materials



Affordable clean water is a problem of advanced materials

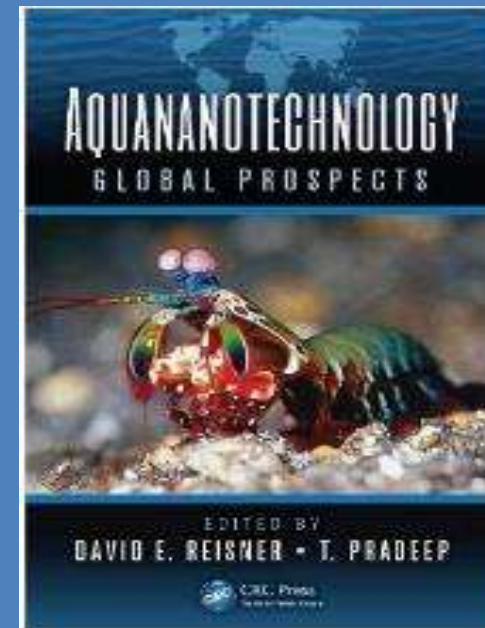
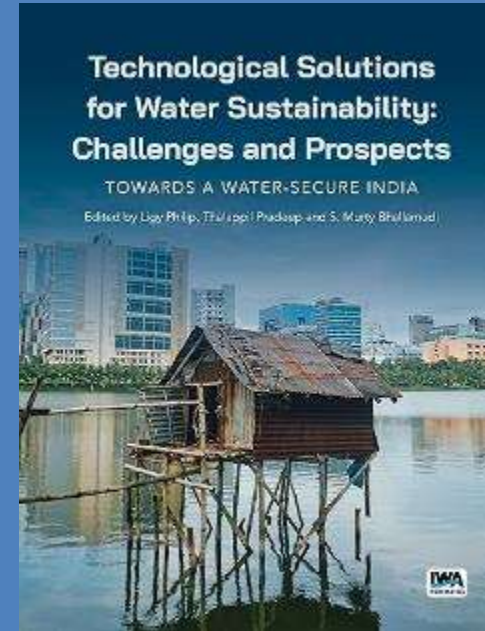
New adsorbents

New sensors

New catalysts

Novel phenomena

New devices

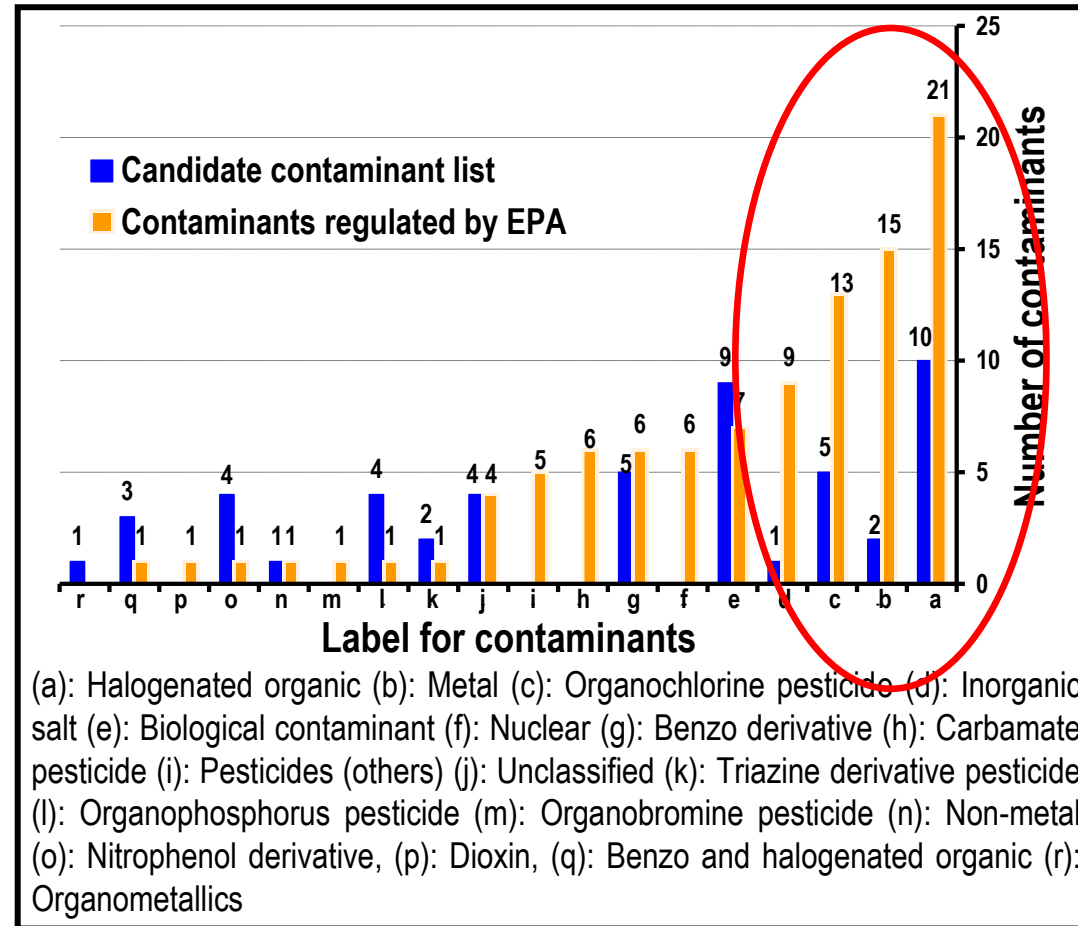


Water purification, history

Important milestones in the history of water purification (1800–2007) from the perspective of noble metal nanoparticles in water treatment (compiled from multiple sources on the World Wide Web).

Year	Milestone
1804	Setup of world's first city-wide municipal water treatment plant (Scotland, sand-filter technology)
1810	Discovery of chlorine as a disinfectant (H. Davy)
1852	Formulation of Metropolis Water Act (England)
1879	Formulation of Germ Theory (L. Pasteur)
1902	Use of chlorine as a disinfectant in drinking water supply (calcium hypochlorite, Belgium)
1906	Use of ozone as a disinfectant (France)
1908	Use of chlorine as a disinfectant in municipal supply, New Jersey
1914	Federal regulation of drinking water quality (USPHS)
1916	Use of UV treatment in municipal supplies
1935	Discovery of synthetic ion exchange resin (B. A. Adams, E. L. Holmes)
1948	Nobel Prize to Paul Hermann Muller (insecticidal properties of DDT)
1959	Discovery of synthetic reverse osmosis membrane (S. Yuster, S. Loeb, S. Sourirajan)
1962	<i>Silent Spring</i> published, first report on harmful effects of DDT (R. Carson)
1965	World's first commercial RO plant launched
1974	Reports on carcinogenic by-products of disinfection with chlorine Formulation of Safe Drinking Water Act (USEPA)
1975	Development of carbon block for drinking water purification
1994	Report on use of zerovalent iron for degradation of halogenated organics (R. W. Gillham, S. F. O'Hannesin)
1997	Report on use of zerovalent iron nanoparticles for degradation of halogenated organics (C-B. Wang, W.-X. Zhang)
1998	Drinking Water Directive applied in EU
2000	Adoption of Millennium Declaration during the UN Millennium Summit (UN Millennium Development Goals)
2003	Report on use of noble metal nanoparticles for the degradation of pesticides (A.S. Nair, R. T. Tom, T. Pradeep)
2004	Stockholm Convention, banning the use of persistent organic pollutants
2007	Launch of noble metal nanoparticle-based domestic water purifier (T. Pradeep, A. S. Nair, Eureka Forbes Limited)

Future of water purification: An enigma with some pointers



Category-wise distribution of contaminants regulated by USEPA and future contaminants

Noble metal nanoparticles for water purification: A critical review, T. Pradeep and Anshup, Invited critical review, Thin Solid Films, 517 (2009) 6441-6478 (DOI: 10.1016/j.tsf.2009.03.195).

World's first nanochemistry-based water purifier

RSC | Advancing the
Chemical Sciences
Chemistry World

Pesticide filter debuts in India

20 April 2007

Kilugudi Jayaraman/Bangalore, India

A domestic water filter that uses metal nanoparticles to remove dissolved pesticide residues is about to enter the Indian market. Its developers at the Indian Institute of Technology (IIT) in Chennai (formerly Madras) believe it is the first product of its kind in the world to be commercialised.

Mumbai-based Eureka Forbes Limited, a company that sells water purification systems, is collaborating with IIT and has tested the device in the field for over six months. Jayachandran Pradeep, a technical consultant to the company, expects the first 1000 units to be sold door-to-door from late May.

Our pesticide filter is an offshoot of basic research on the chemistry of nanoparticles. Thirupathi Pradeep who led the team at IIT Chennai told Chemistry World. He and his student Sreenivasan Pillai discovered in 2003 that nanocarbons such as carbon nanotubes (CNTs) completely break down into metal halides and amorphous carbon upon reaction with gold and silver nanoparticles.

Pradeep said this prompted them to extend their study to include organochlorine and organophosphorous pesticides, whose presence in water is posing a health risk in rural India. In research funded by the Department of Science and

Technology in New Delhi, his team found¹ that gold and silver nanoparticles loaded on alumina were indeed able to completely remove endosulfan, malathion and chlorpyrifos - three pesticides that have been found in drinking water supplies.

Use and recycle

The next

Pradeep

Mumbai

nanotech

novel. Gastry

Chemistry world
First ever
nanotechnology
product for clean
water

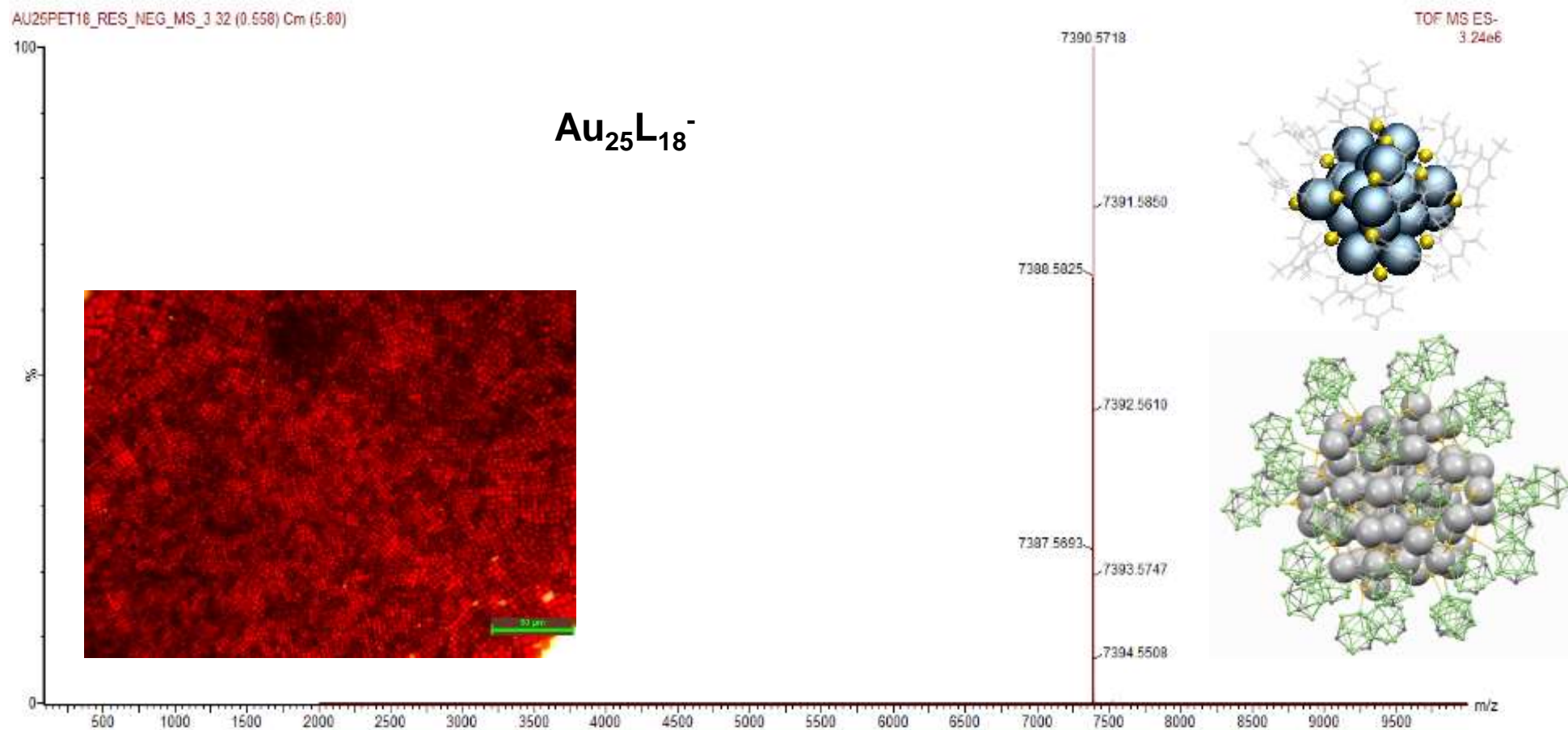


A plant to make supported nanomaterials for water purification; with capacity of 4.5 tons per month, 2007

1. Patents: A method of preparing purified water from water containing pesticides, **Indian patent 200767**
 2. Extraction of malathion and chlorpyrifos from drinking water by nanoparticles, **US 7,968,493** A method for decontaminating water containing pesticides, **EP 17,15,947**
- Product is marketed now by a Eureka Forbes Ltd.
Several new technologies are now available



Nanomaterials are now atomically precise



T. Pradeep et. al. *Acc. Chem. Res.* 2018; 2019.

Clean water for everyone



ACS Sustainable Chemistry & Engineering Editorial,
December 2016

Water positive materials

PNAS PNAS PNAS

Biopolymer-reinforced synthetic granular nanocomposites for affordable water purification

Mohan Udhaya Sankar¹, Sahaja Aigal,
Kamalesh Chaudhari, and Thalappil Pradeep

¹Unit of Nanoscience and Thematic Unit of Excellence

Edited by Eric Hoek, University of California, Los Angeles

Creation of affordable materials for constant clean drinking water is one of the most promising ways to ensure water for all. Combining the capabilities of nanocomposites to scavenge toxic species such as heavy metals and other contaminants along with the above-mentioned materials to provide affordable, all-inclusive drinking water purification without electricity. The critical problem is the synthesis of stable materials that can reliably function in the presence of complex species in drinking water that deposit and cause scaling on surfaces. Here we show that such constant materials can be synthesized in a simple and effective fashion without the use of electrical power. The nanocomposites have sand-like properties, such as higher shear strength and stability. These materials have been used to develop a water purifier to deliver clean drinking water. The ability to prepare nanostructures at ambient temperature has wide relevance for water purification.

hybrid | green | appropriate technology | frugal science | developing world



Anil Kumar,

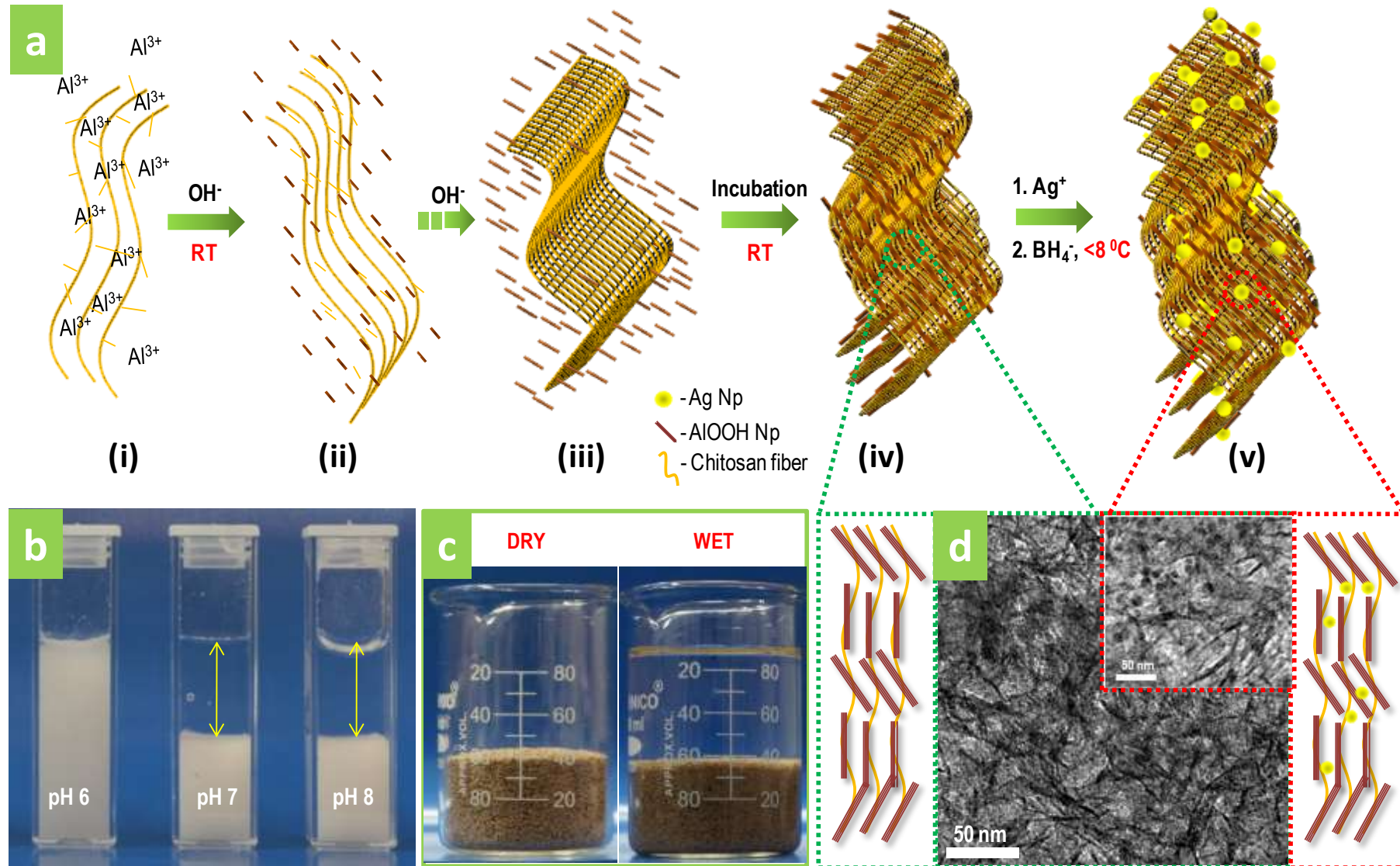
6, India

September 21, 2012

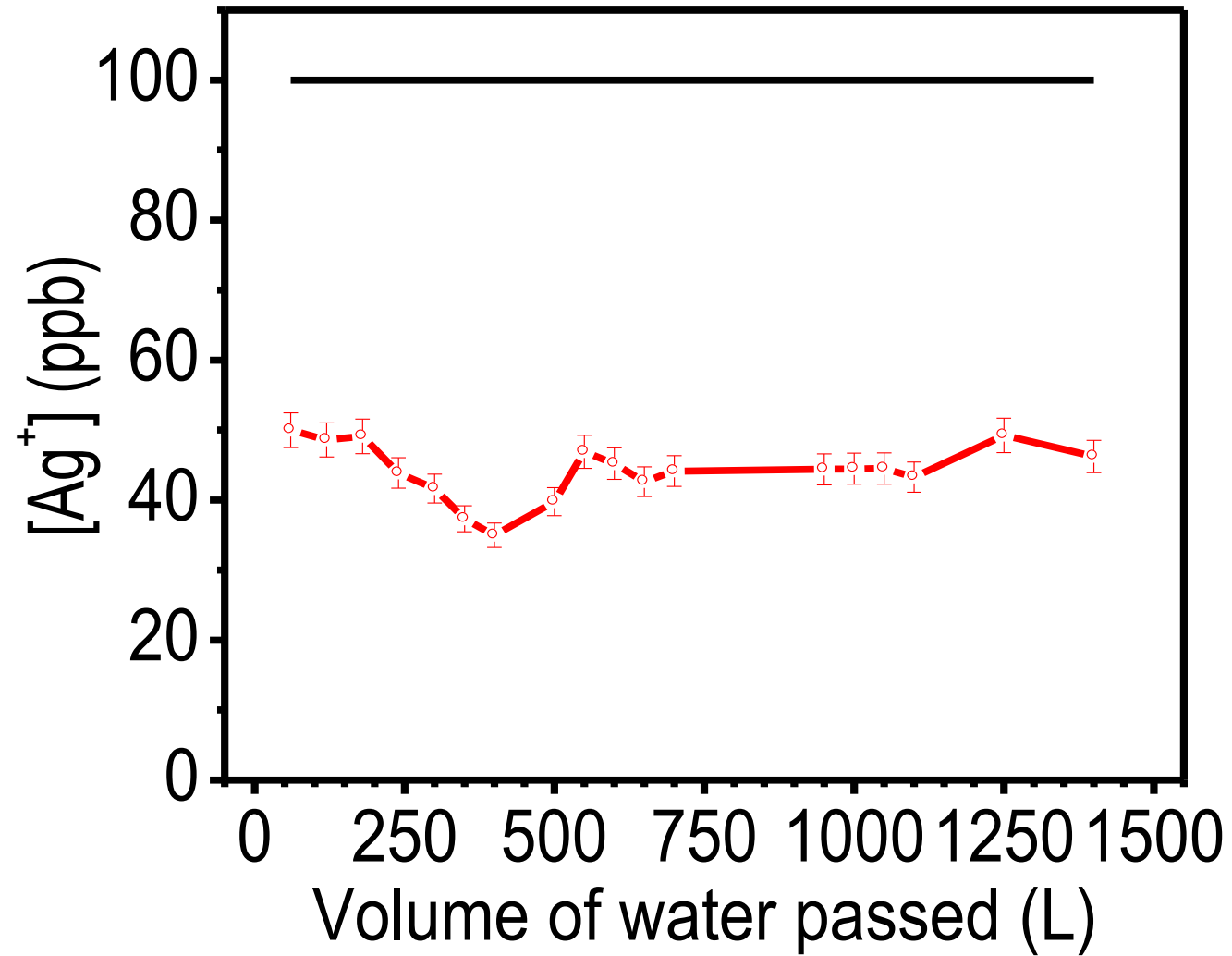
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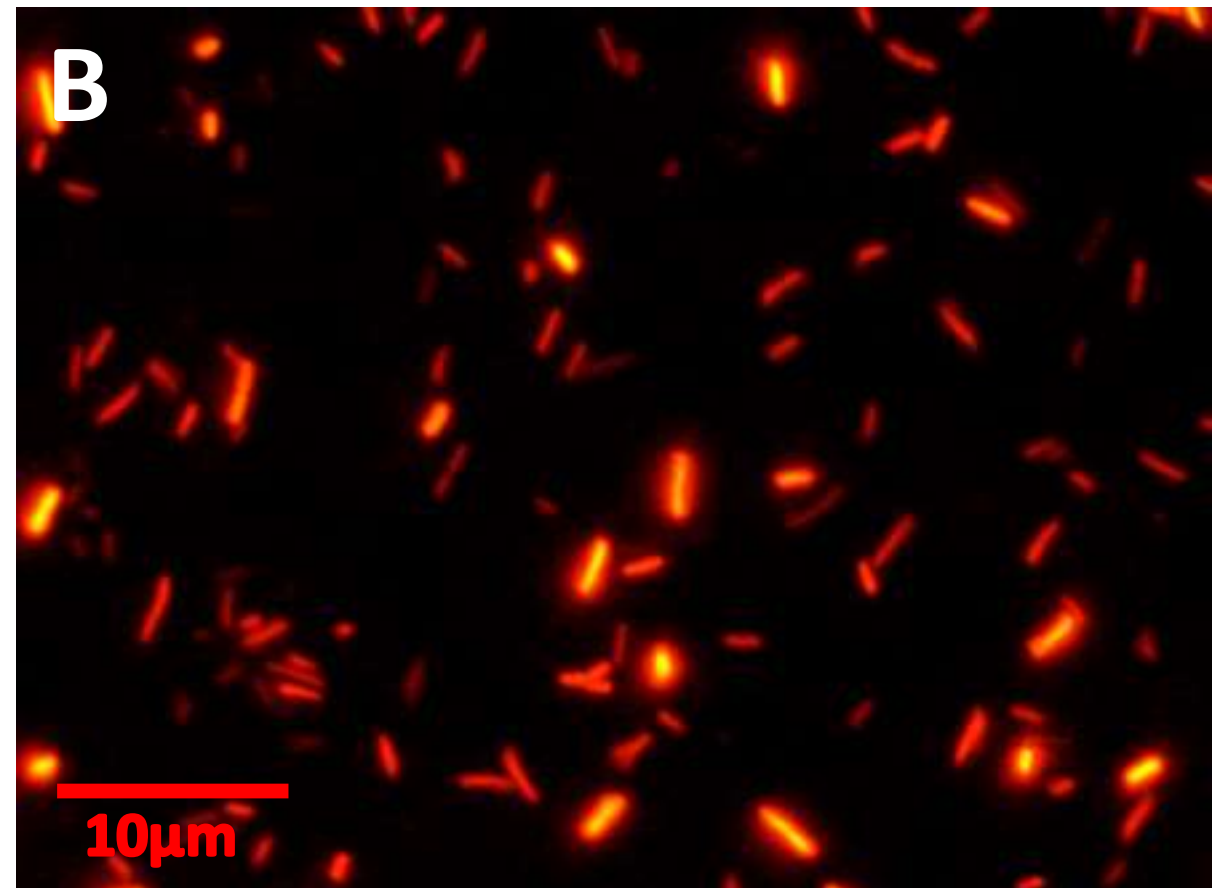
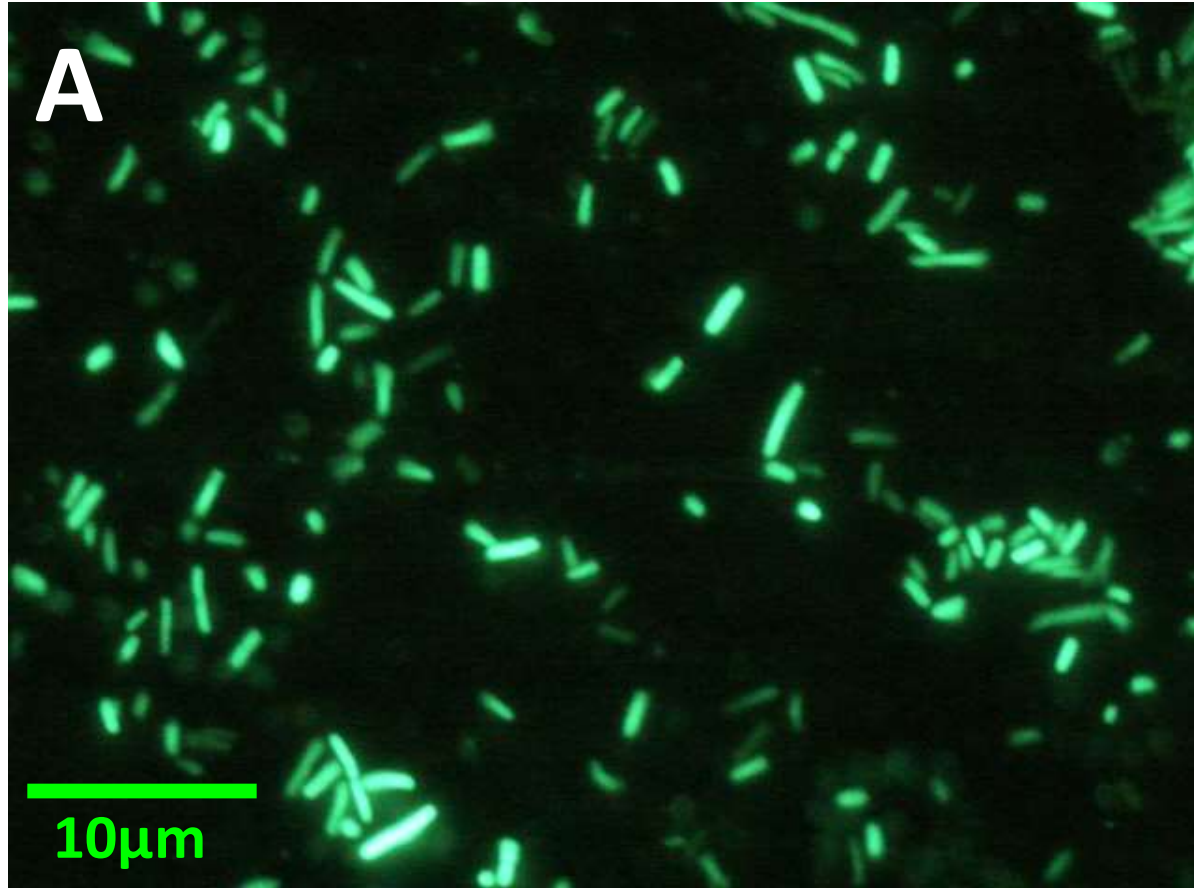
How to make?



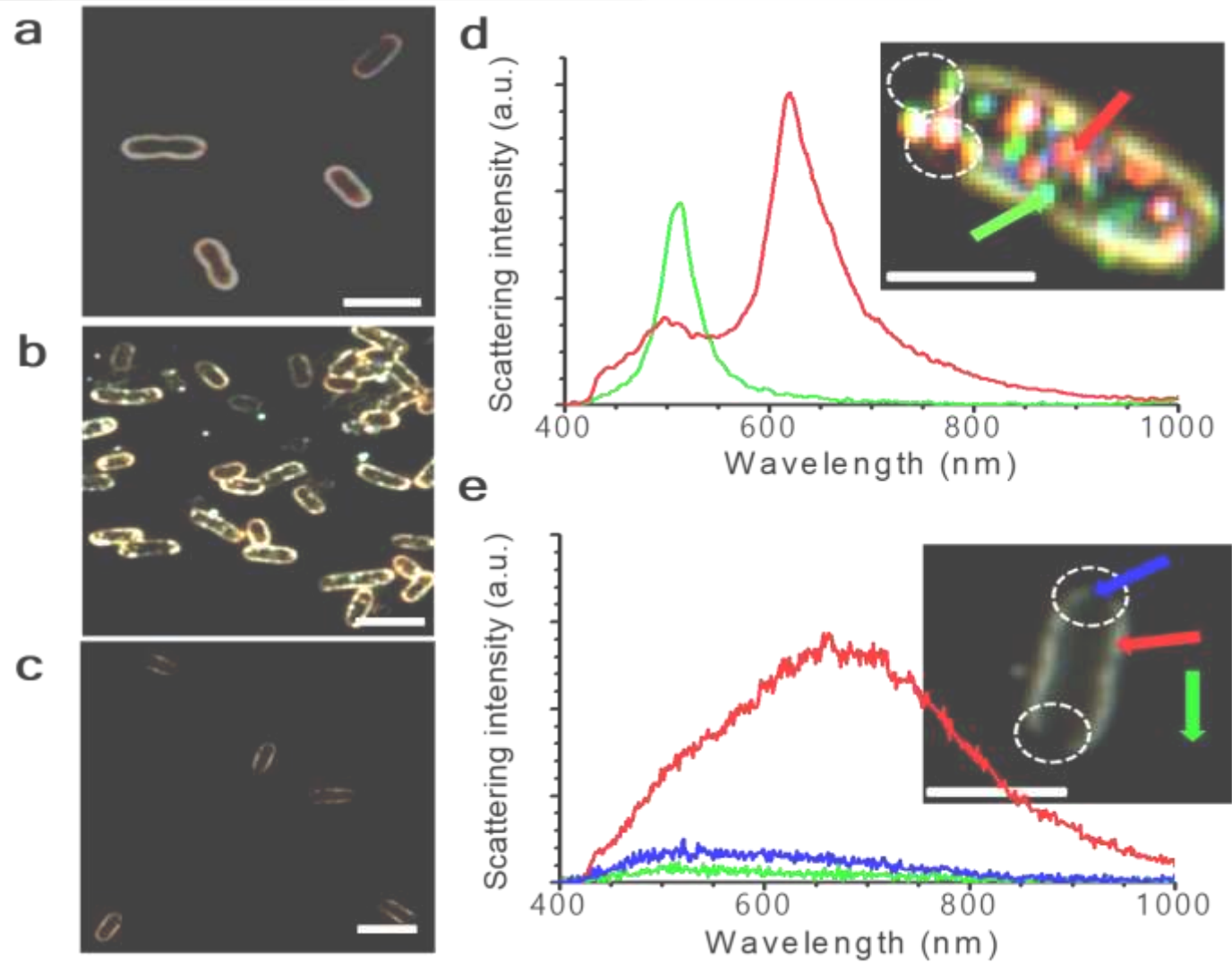
What is special?



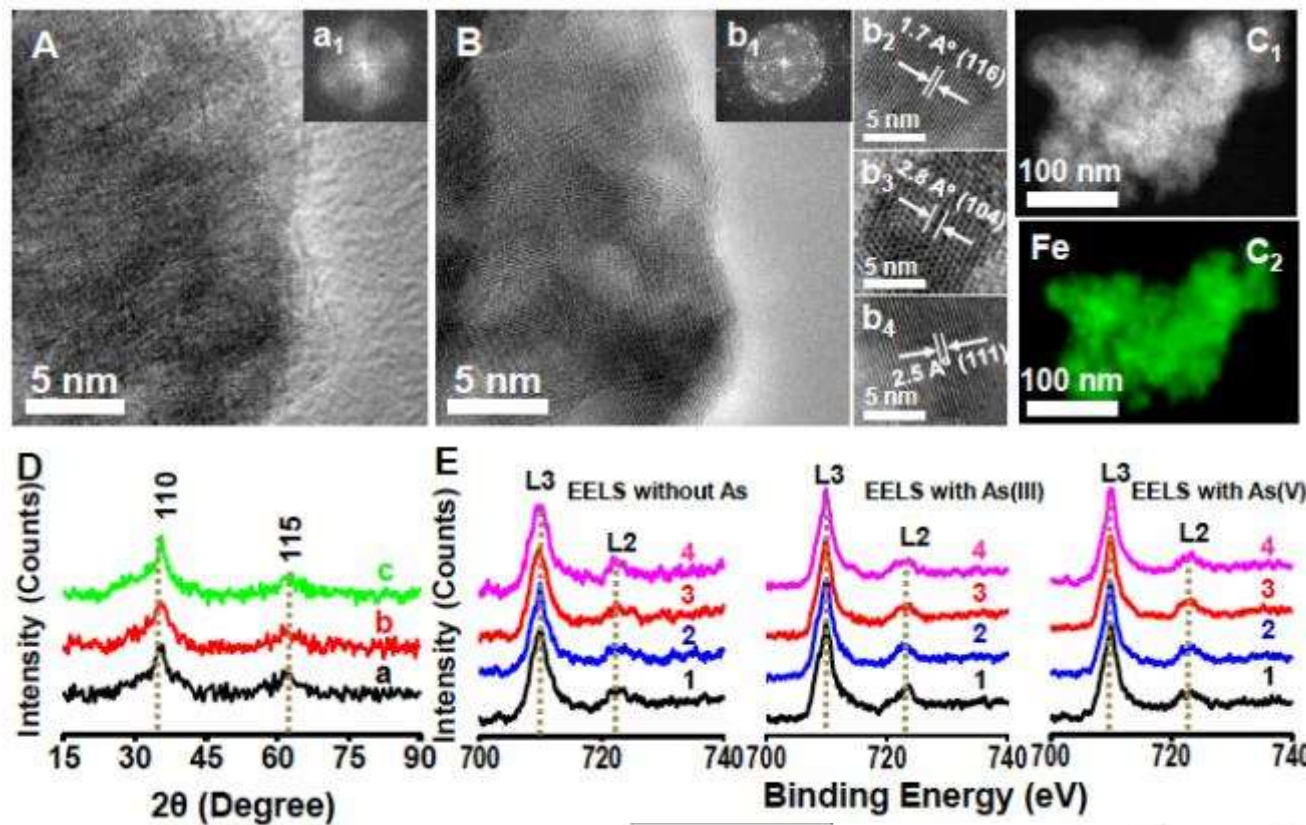
Live/dead staining experiments



No nanotoxicity



Variety of materials



www.advmat.de

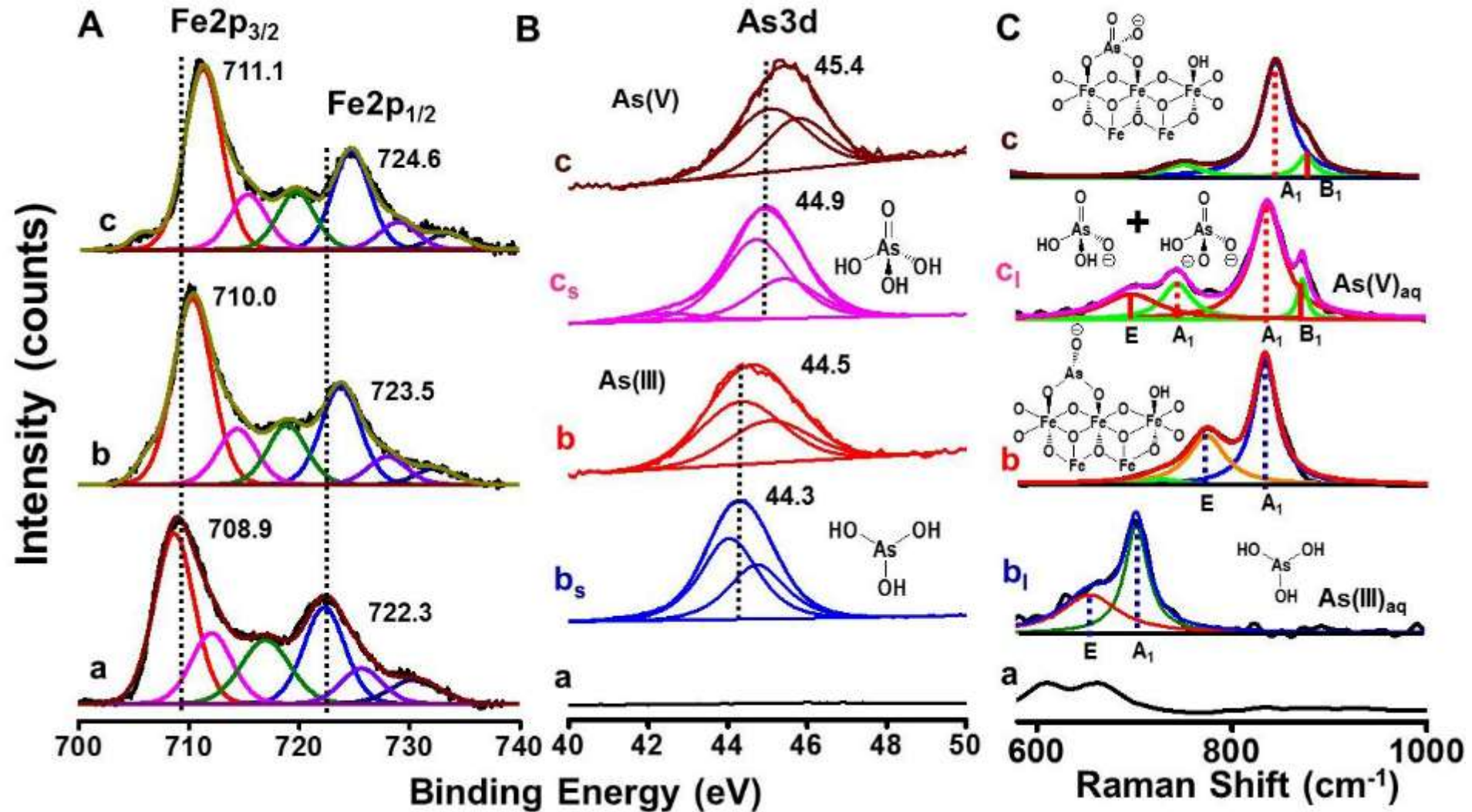
Author Pr ADVANCED MATERIALS

Confined Metastable 2-Line Ferrihydrite for Affordable Point-of-Use Arsenic Free Drinking Water

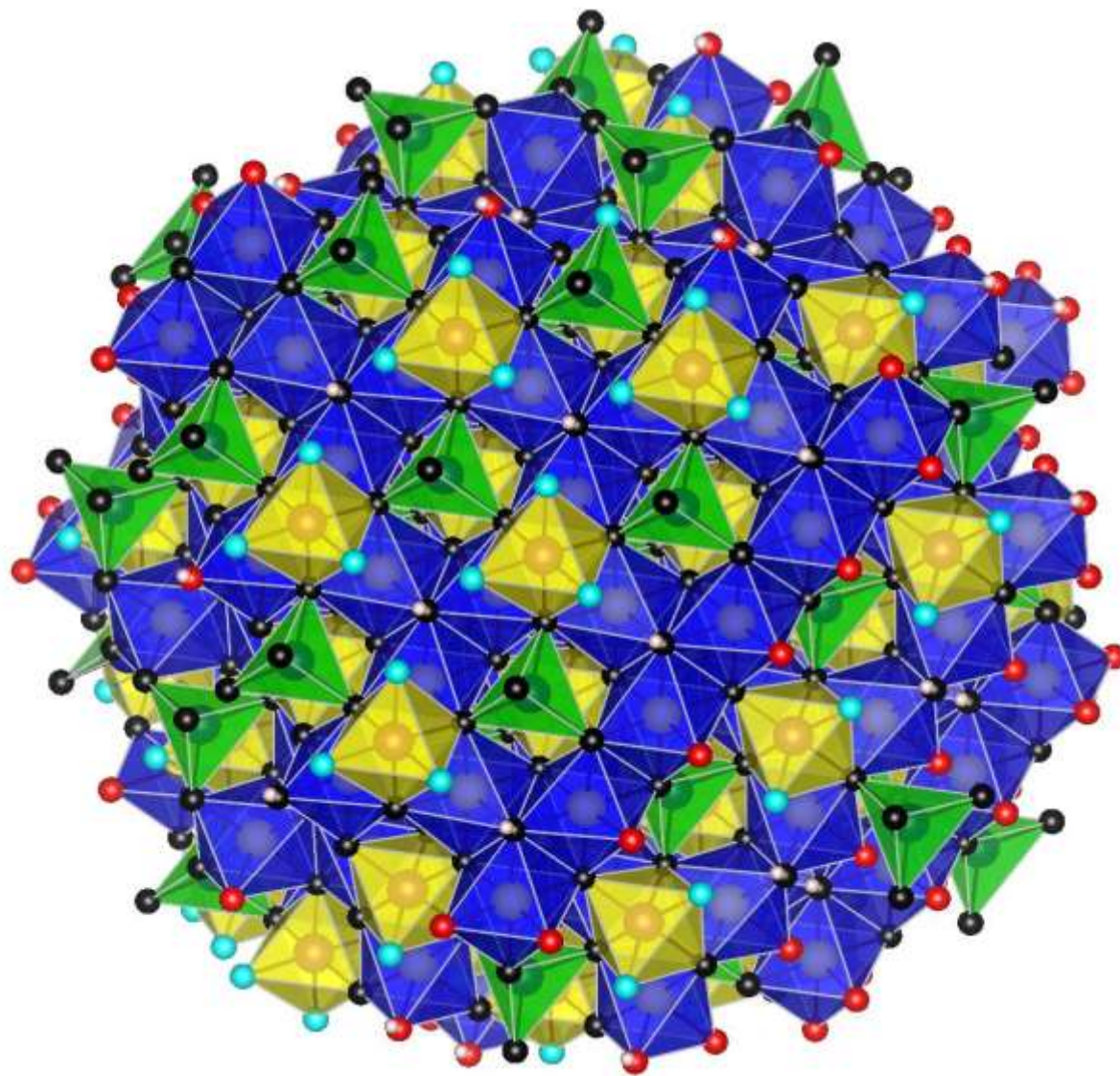
By Avula Anil Kumar, Anirban Som, Paolo Longo, Chennu Sudhakar, Radha Gobinda Bhui, Soujit Sen Gupta, Anshup, Mohan Udhaya Sankar, Amrita Chaudhary, Ramesh Kumar, and T. Pradeep*

Communication

Mechanism – molecular tools

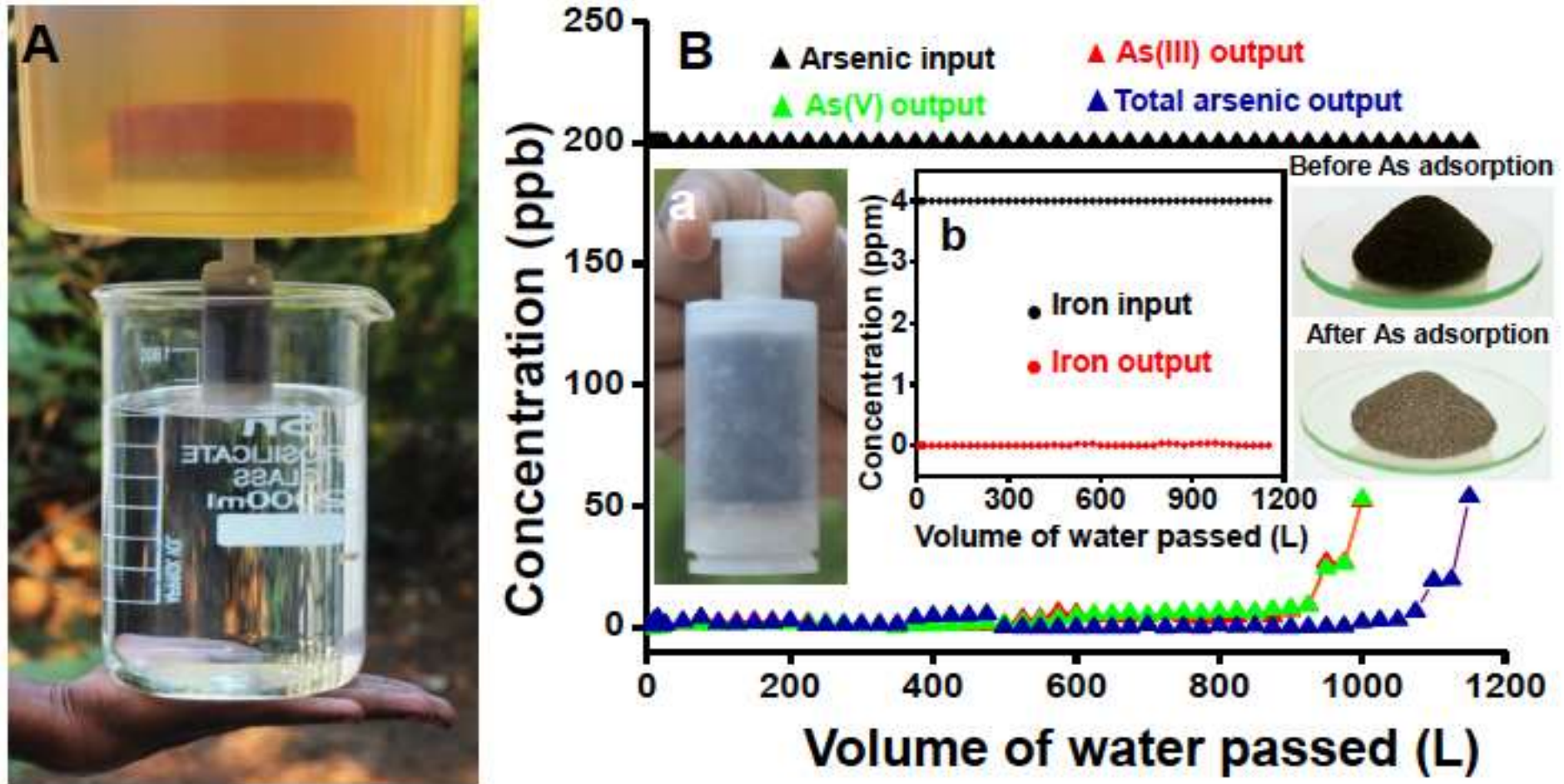


Modeling surfaces



Chennu Sudhakar, et al. *ACS Sustainable Chemistry & Engineering*, 6 (2018) 9990-10000.

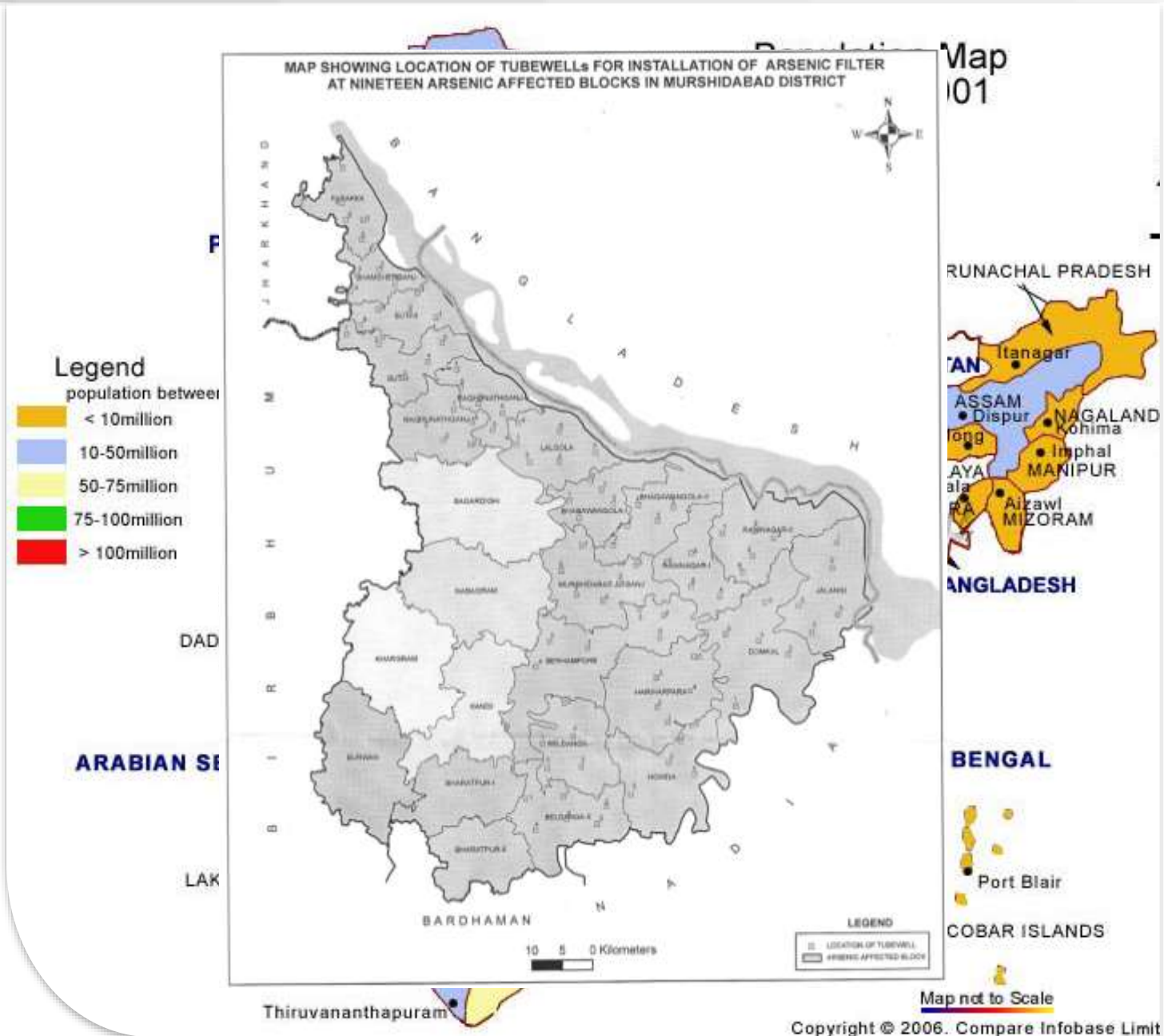
Lab studies



Initial pilot studies



Larger pilot studies



Changing the dynamics in the field



Existing plant in 40 cents

- Existing unit for iron and arsenic removal – 20 m³/h
- Uses activated alumina and iron oxide (old generation of adsorbents)



New plant in 3 cents

- Existing unit for iron and arsenic removal – 18 m³/h
- Uses iron oxyhydroxide (new generation of adsorbents)
- Input arsenic concentration: 168 ppb
- Output arsenic concentration: 2 ppb

Completed 3 years maintenance (stipulated: 2 years)
for 330 bamboo unit project in Nadia, WB



Minimum uptime: 91%, Maximum: 98%
Only 4/330 have reported arsenic above 10 ppb
Benefiting over 100,000 children and villagers

Glimpse of Installed units (330 nos)

Implementation - From 25 KLD to 1 MLD



Large water supply schemes
Capacity: above 1 MLD

5 schemes in use across India



Retrofitted Water Purification Plant
Capacity: 0.1-1 MLD

Over 180 units in use across India

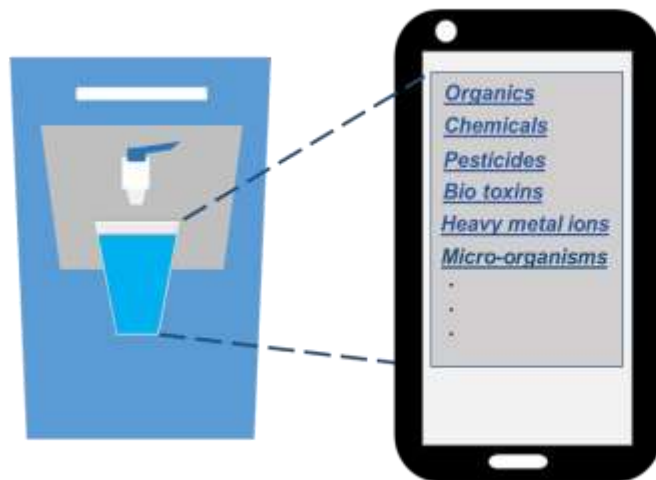


Clean water at 2.1 paise per litre!

Calculation for the Tariff to be collected for treated water (Revision if Required)			
	Design population	1,071	Plant capacity/70 LPCD
Sr.No.	Item/Description	Cost / Quantity	Remarks
1	Cost of Replacement of Iron removal media	56400	After minimum two years if Iron concentration is more than 5 ppm. But iron concentration is more than 5 ppm at only two to three places. Therefore media may work for 3 years also.
2	Cost of Replacement of Arsenic removal media	978660	After minimum two years if Arsenic concentration is more than 100 ppb. But arsenic concentration is more than 100 ppb at only two to three places. Therefore media may work for 3 years also.
3	Cost of replacement of Activated Carbon	28560	
4	Total cost of Replacement of media	1063620	After minimum two years.
5	Total cost of Replacement of media for one year	531810	
6	Plant capacity	75000	ltr per day
7	Design population	1,071	Plant capacity/70 LPCD
8	Cost per liter of water	2.1 Paise per ltr	0.025 cents
9	Cost of replacement of media	1.36	Rs. per head per day =Media replacement cost per year/365/Design population
		40.80	per head per month for 70 LPCD water

Smart water purifiers and big data

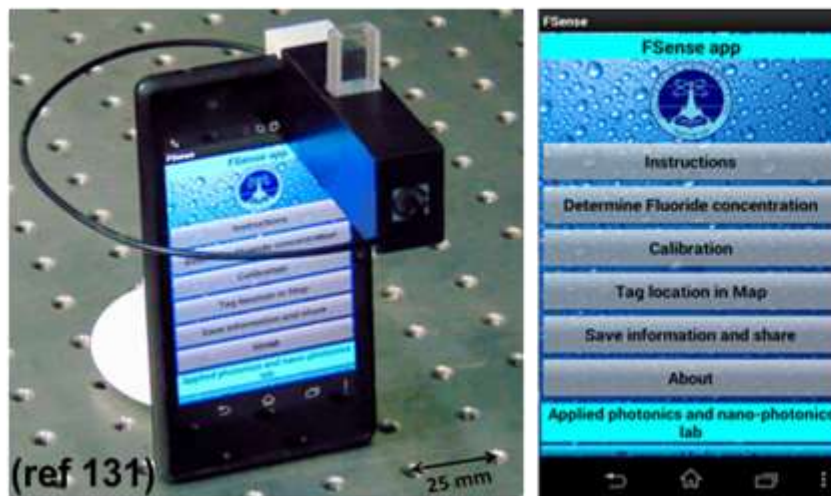
Smart Water Purifiers linked to IoT



Global Map of Water Health



Cost-effective sensor accessory for point-of-use applications



IoT-enabled sensing for households and distribution networks



Waste management

- Adsorbents conform to toxicity characteristic leaching procedure
- Elemental waste goes back to local environment
- Safe disposal of arsenic (or any other) laden waste
- Additional protection could be considered, if necessary
- Exploring viable uses

Now they are across the country



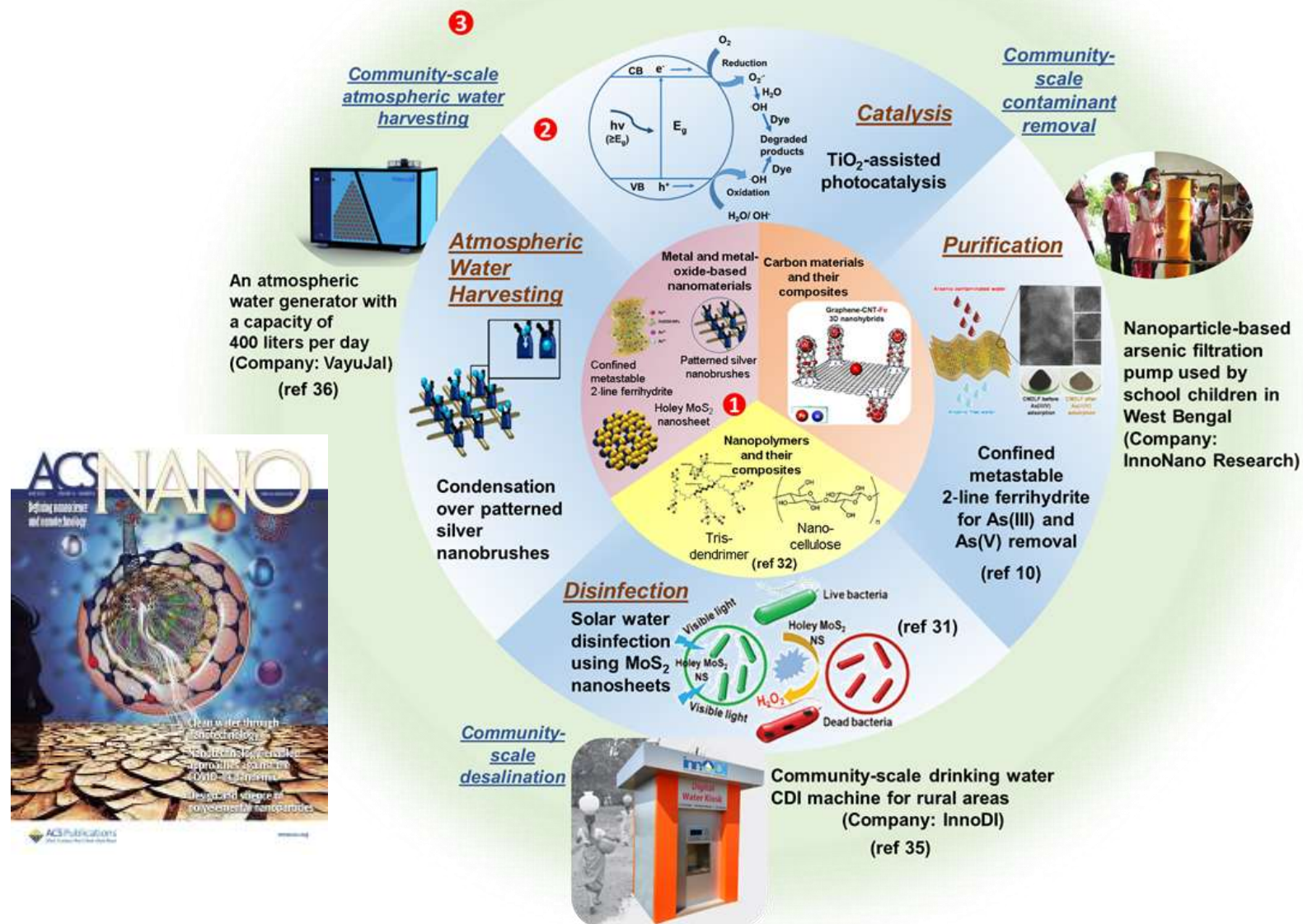
Components of IoT architecture implemented by DWSS, GoP



Typical IoT architecture comprises various sensors and meters, communication gateway, Cloud Server, SMS gateway, Webservices and mobile phone application for operator



Evolution of materials to products



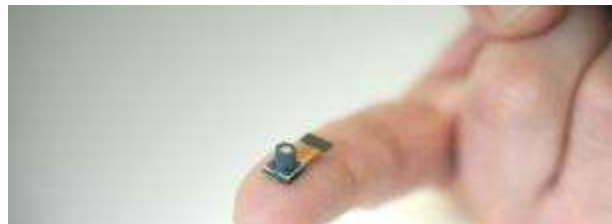
Sensors and new opportunities



Analog/Grating
Equipment
\$ 5~6 Billion (2017)
a few **100k units** (2017)



**Ultra compact Low Cost
Spectral Sensor Module**
~ **Billions units** (? 2027)

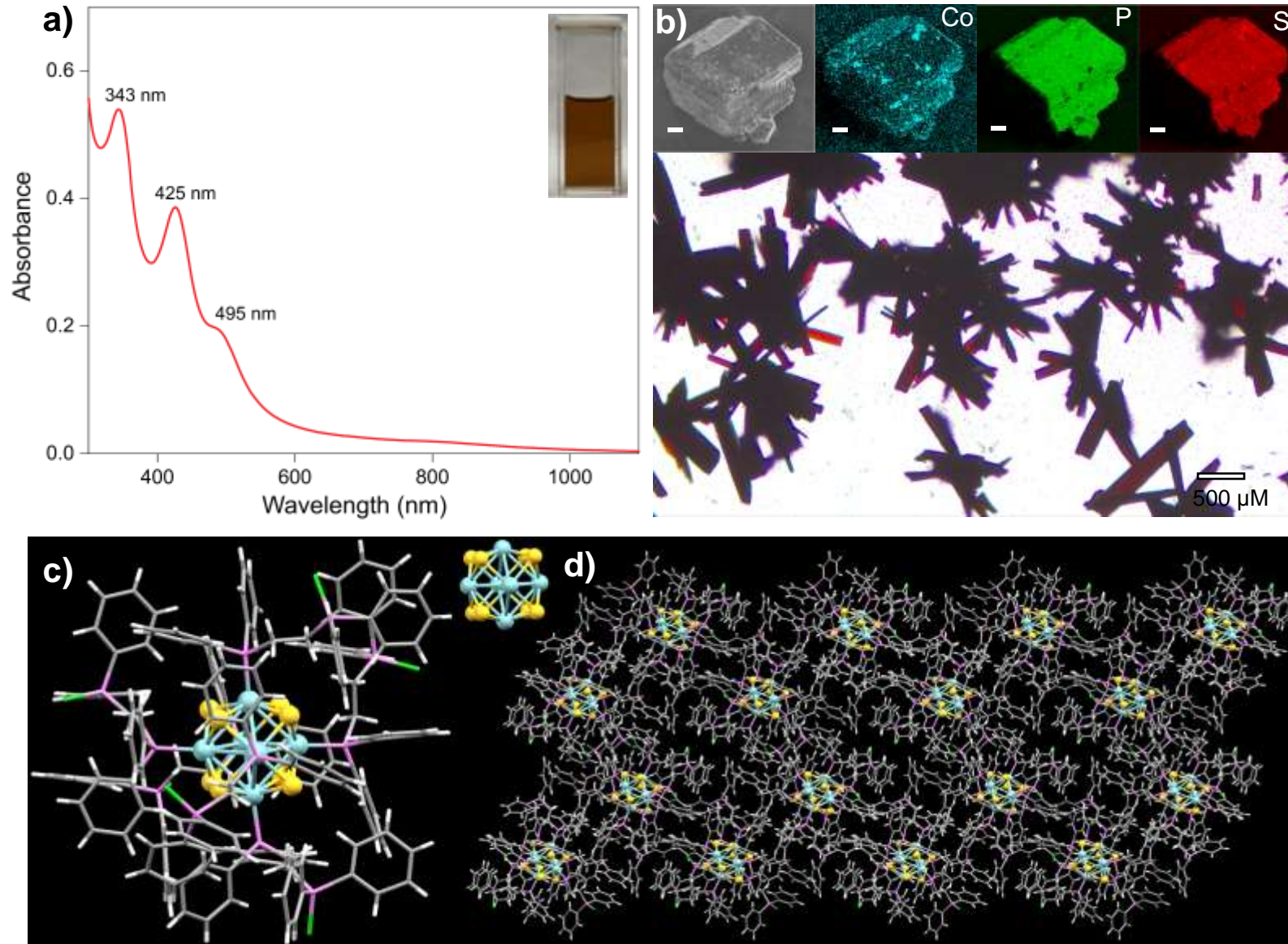


Water quality measurement – In the pipeline

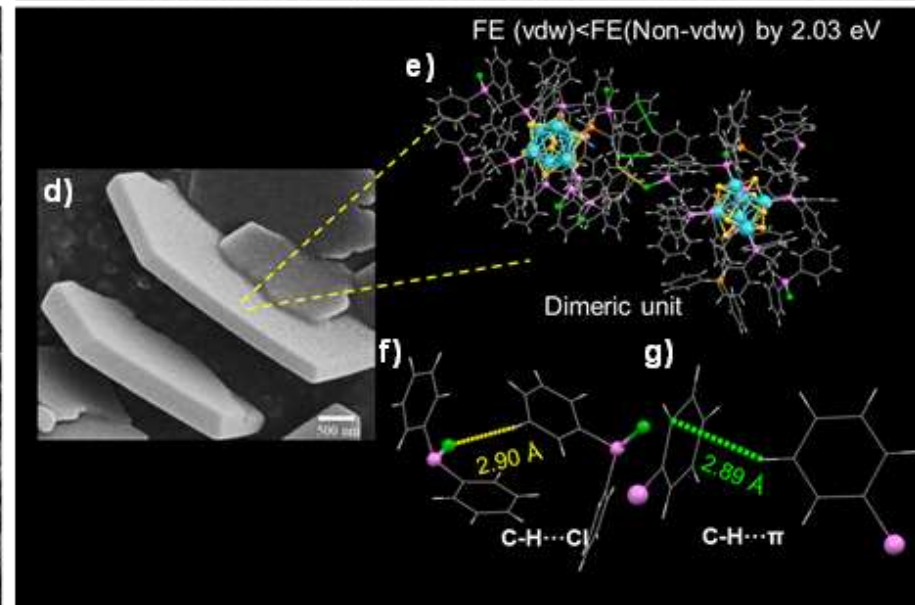
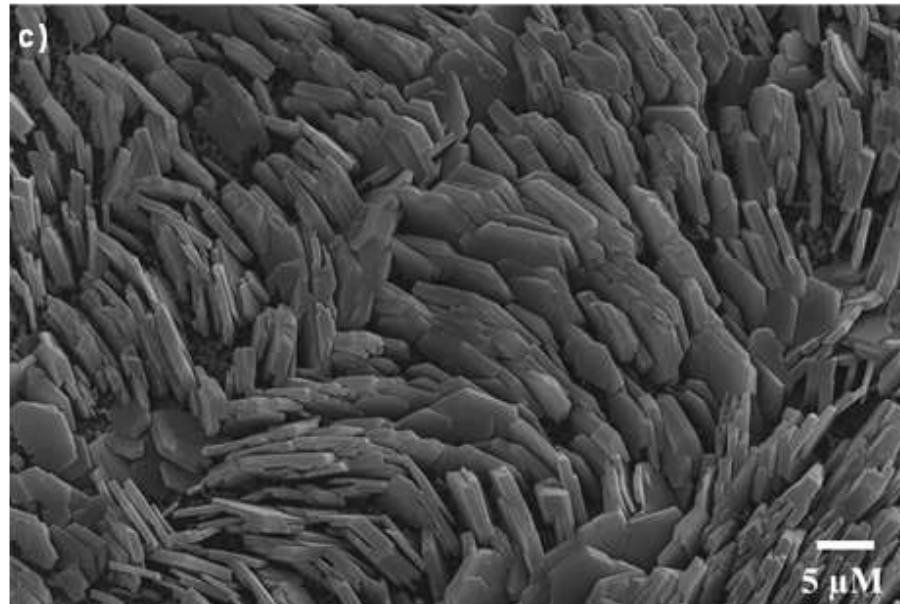
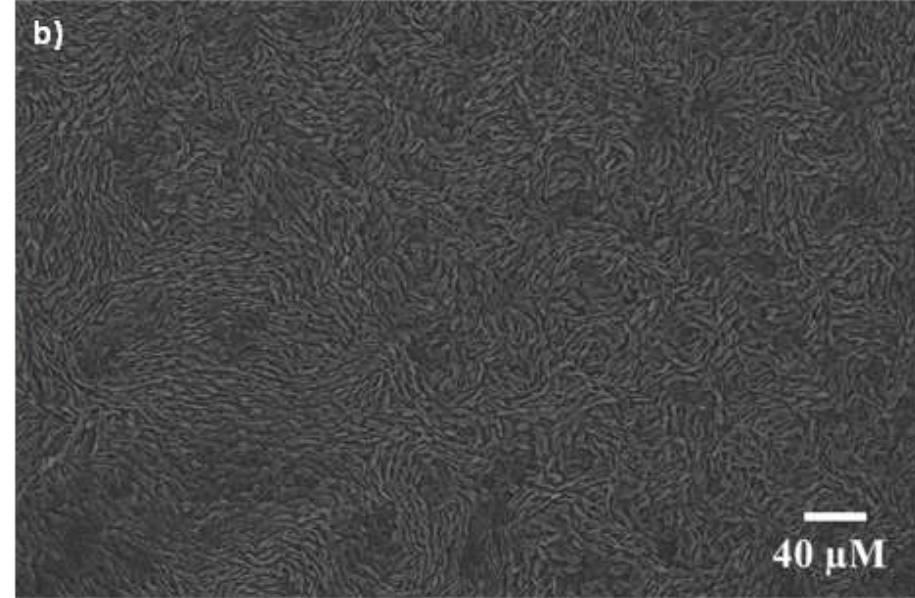
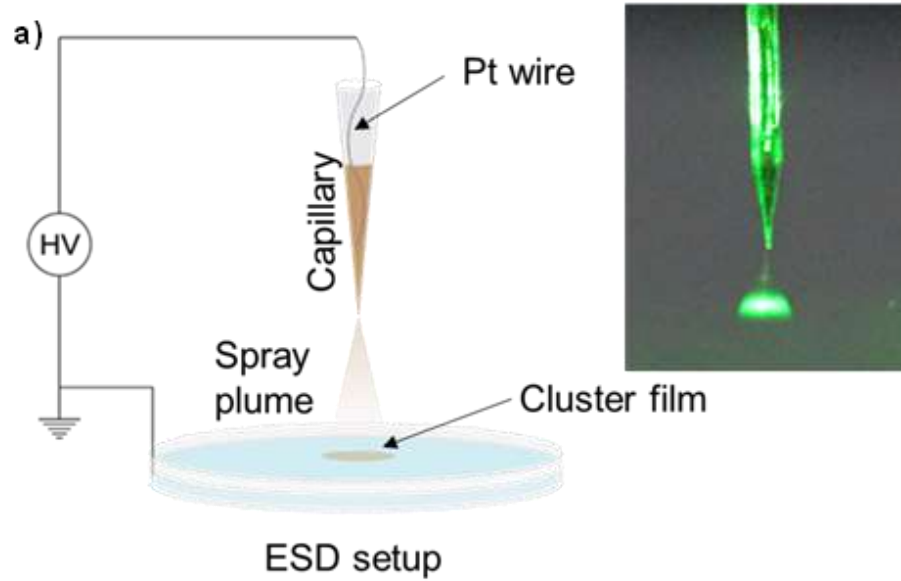
nano λ

New electrodes - Aligned nanoplates of Co_6S_8

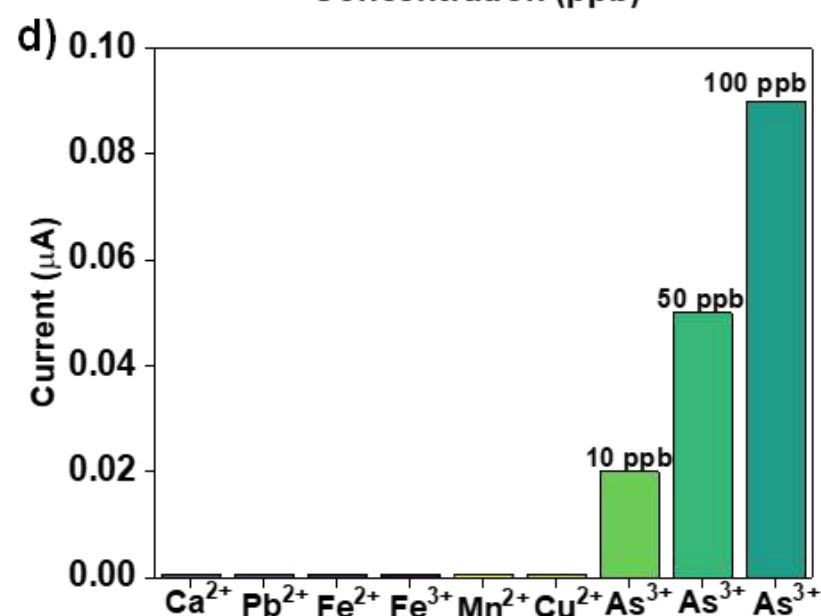
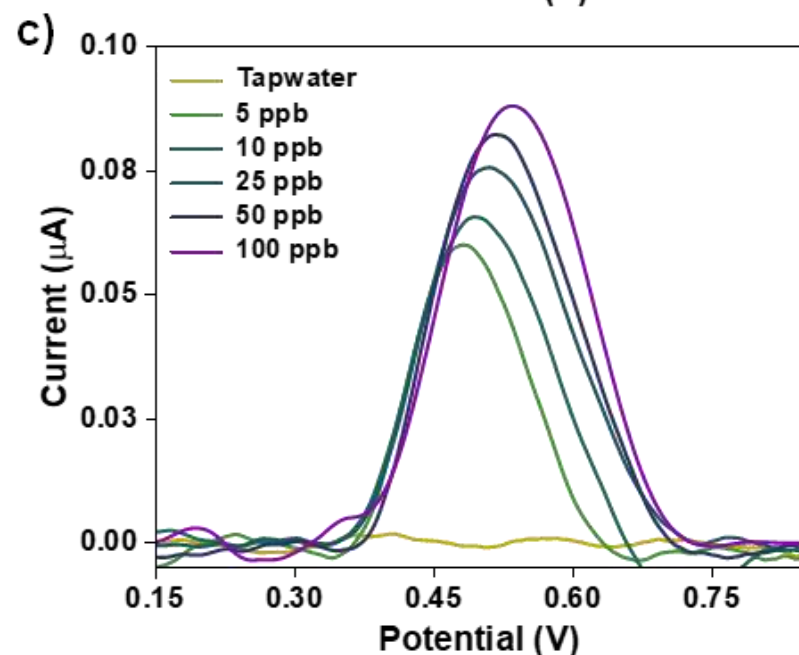
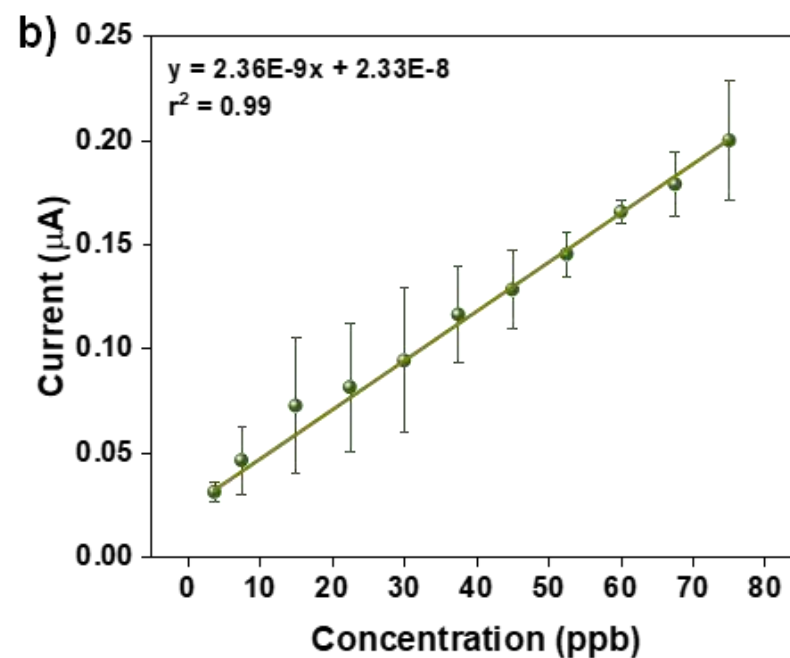
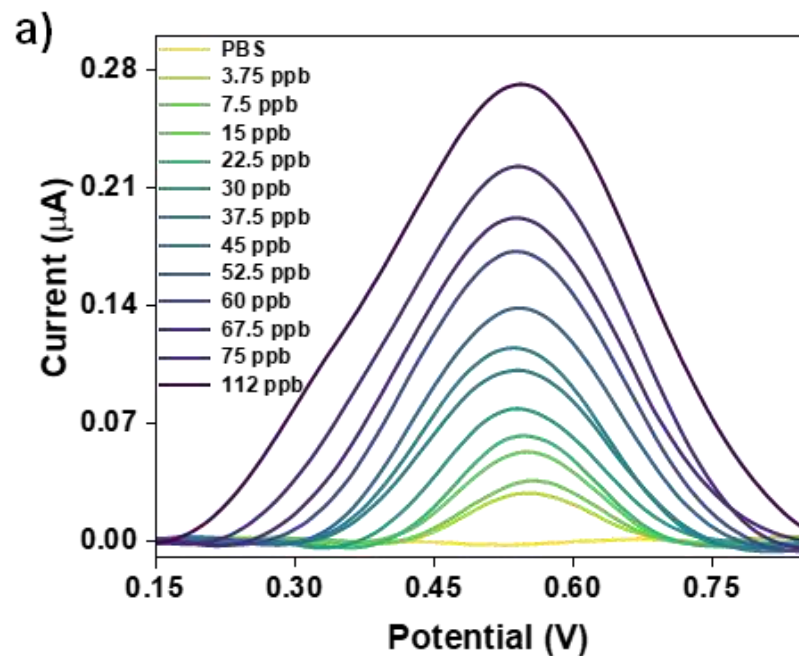
1,2-bis(diphenylphosphino)ethane (DPPE)



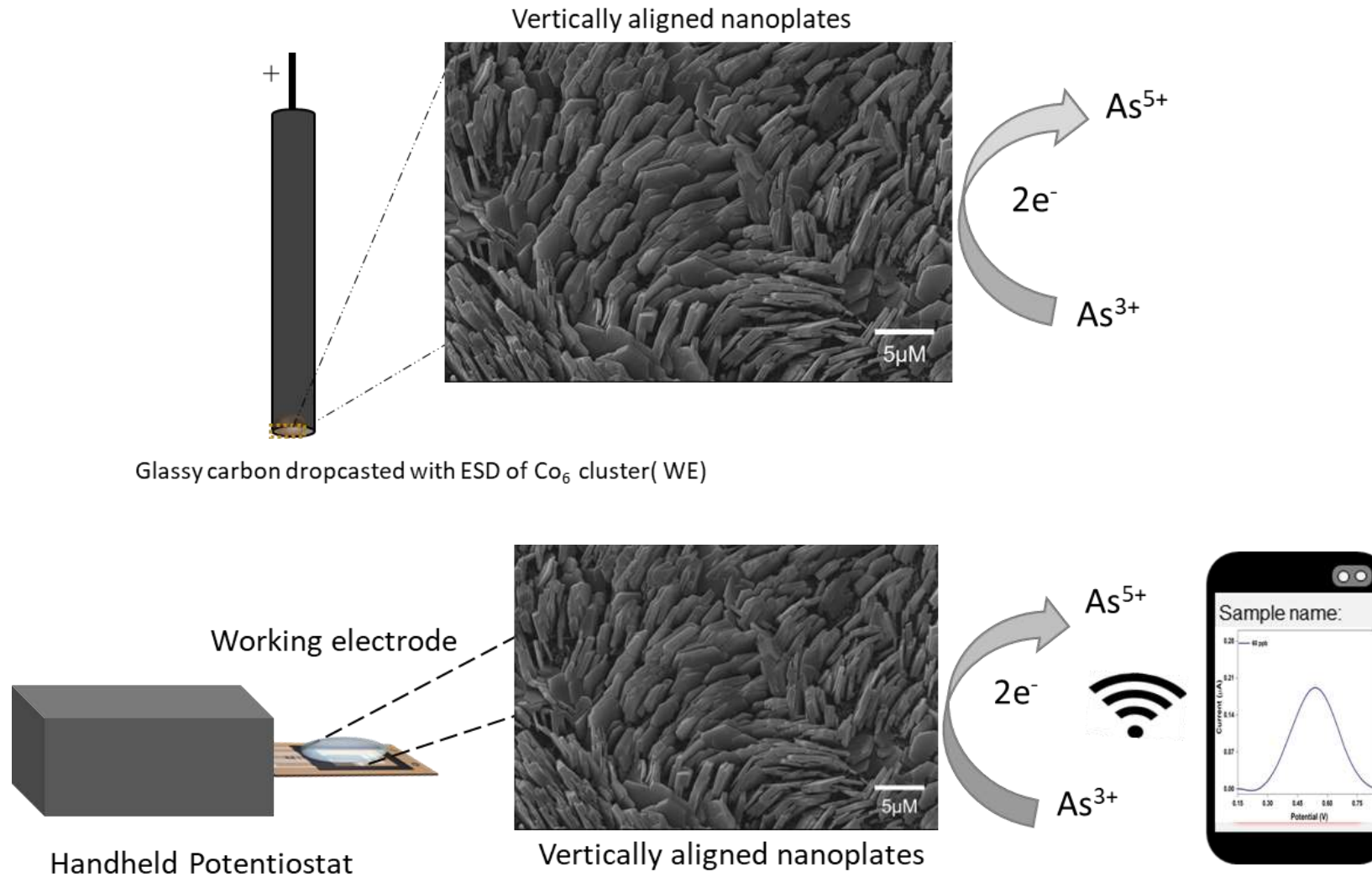
Electrospray deposition



Sensing



Working electrode



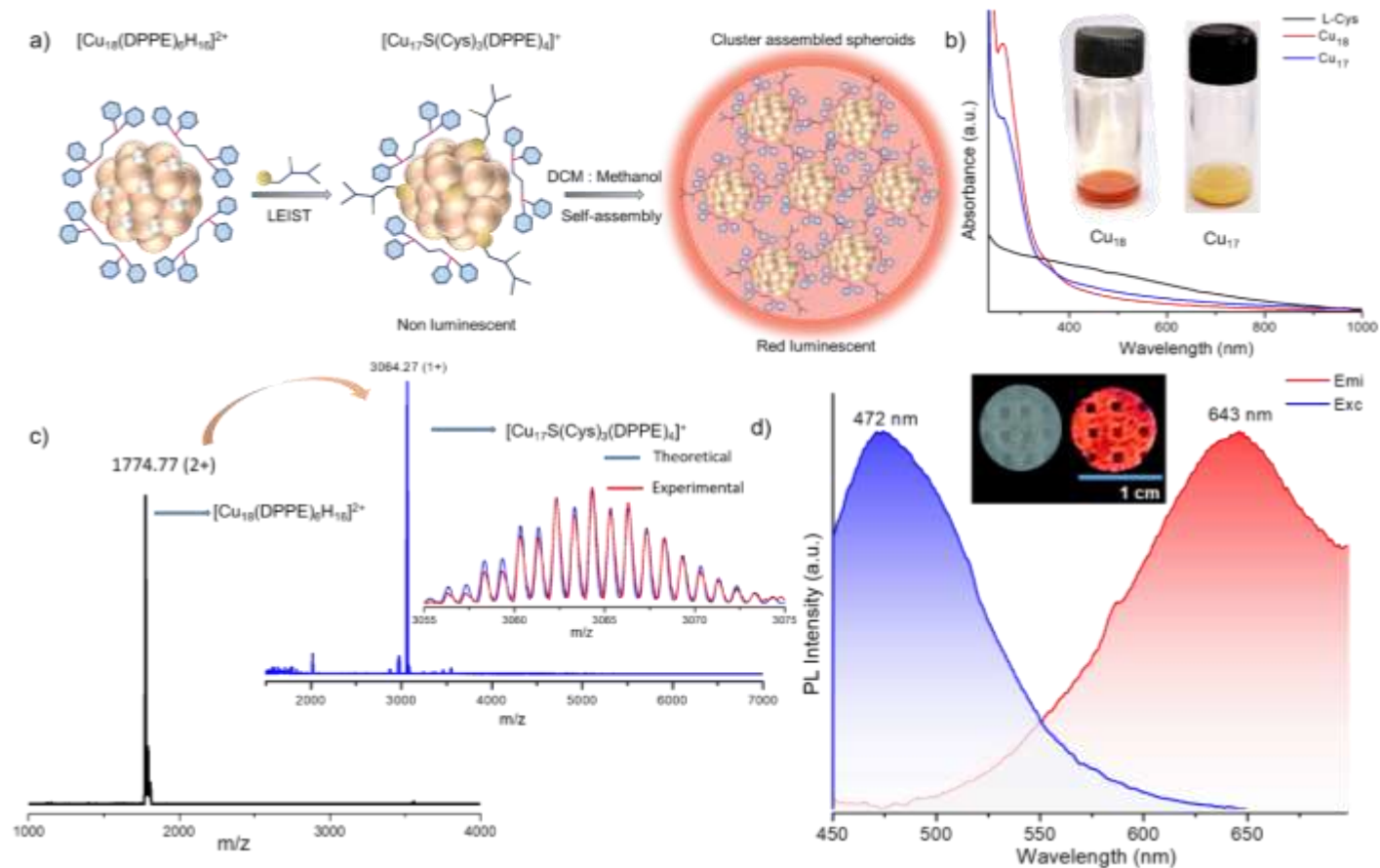
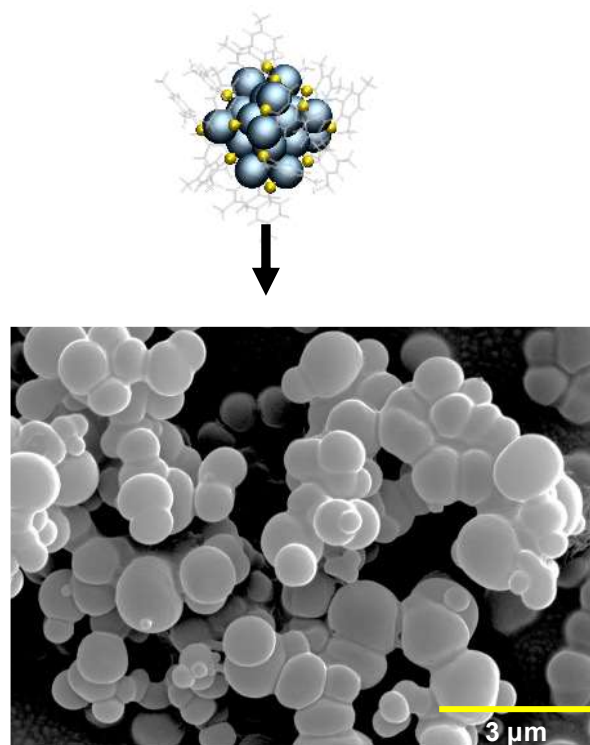
Anagha Jose et al. *ACS Materials Lett.*, 5 (2023) 893–899.

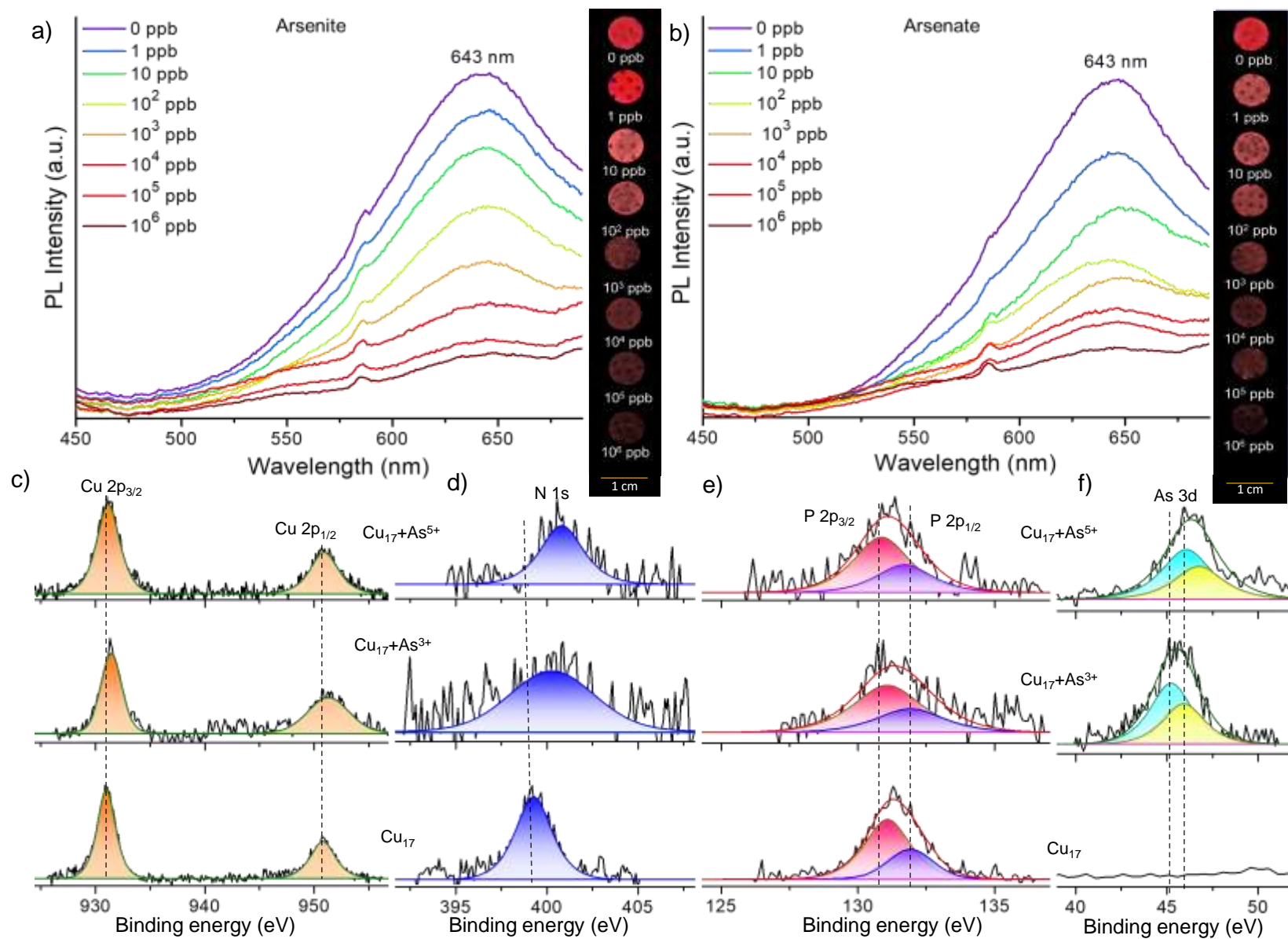
Cysteine-Protected Antibacterial Spheroids of Atomically Precise Copper Clusters for Direct and Affordable Arsenic Detection from Drinking Water

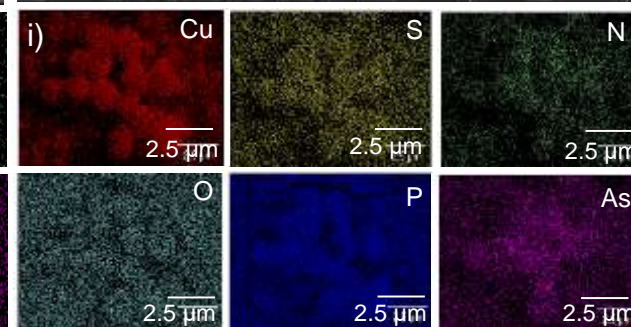
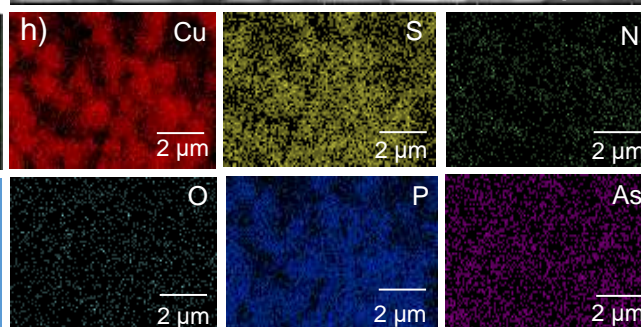
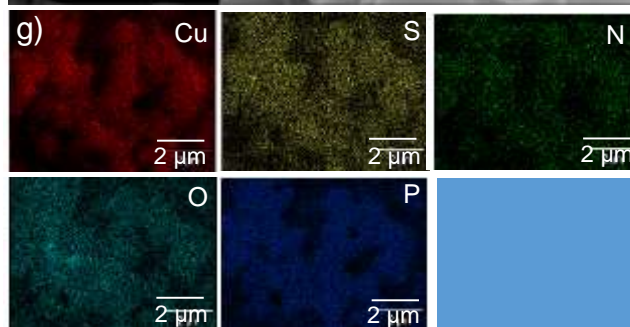
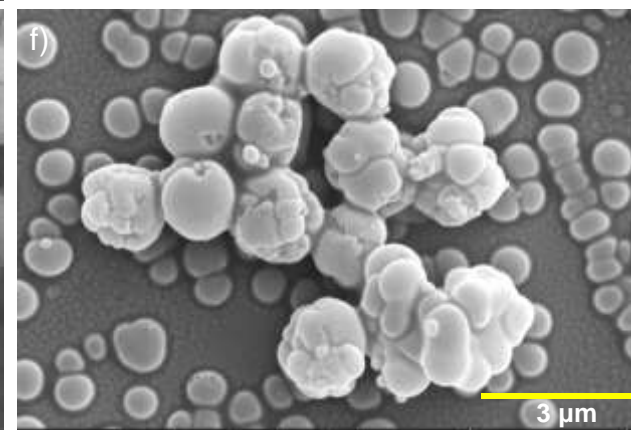
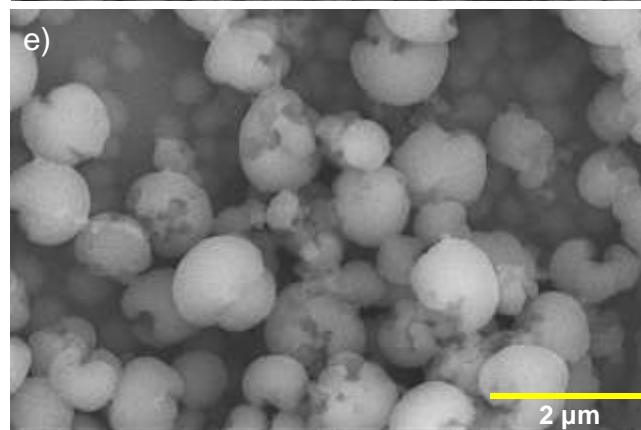
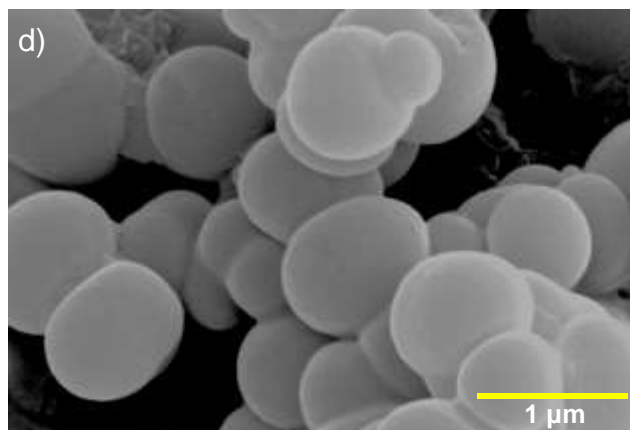
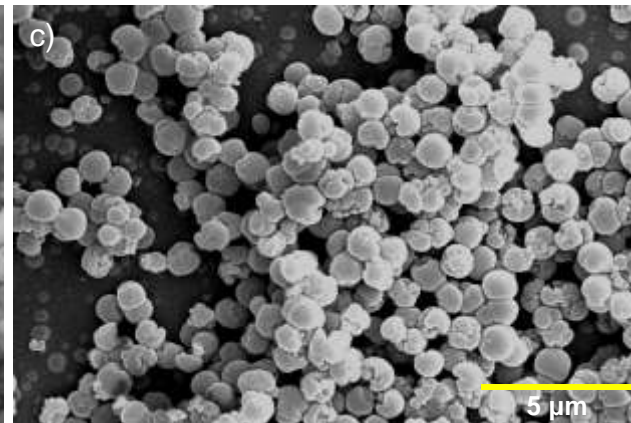
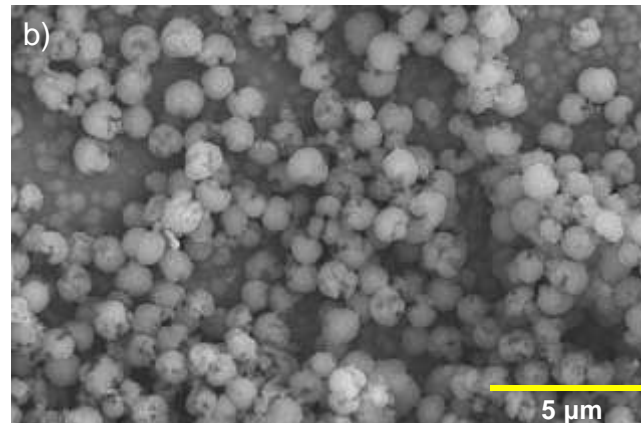
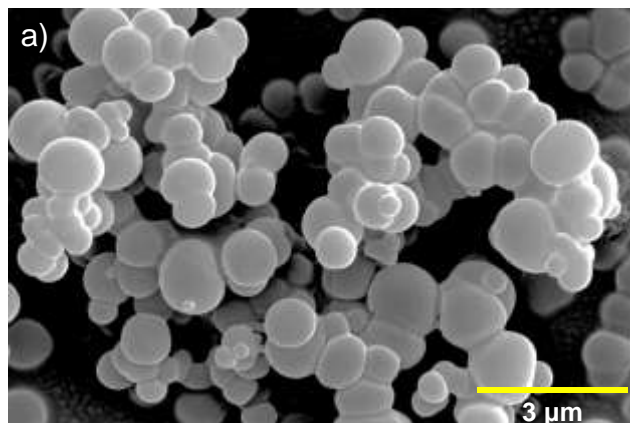
Jenifer Shantha Kumar, Arijit Jana, Jayathraa Raman, Hema Madhuri Veera, Amoghavarsha Ramachandra Kini, Jayoti Roy, Saurav Kanti Jana, Tiju Thomas, and Thalappil Pradeep*

Cite This: <https://doi.org/10.1021/acs.estlett.4c00264>

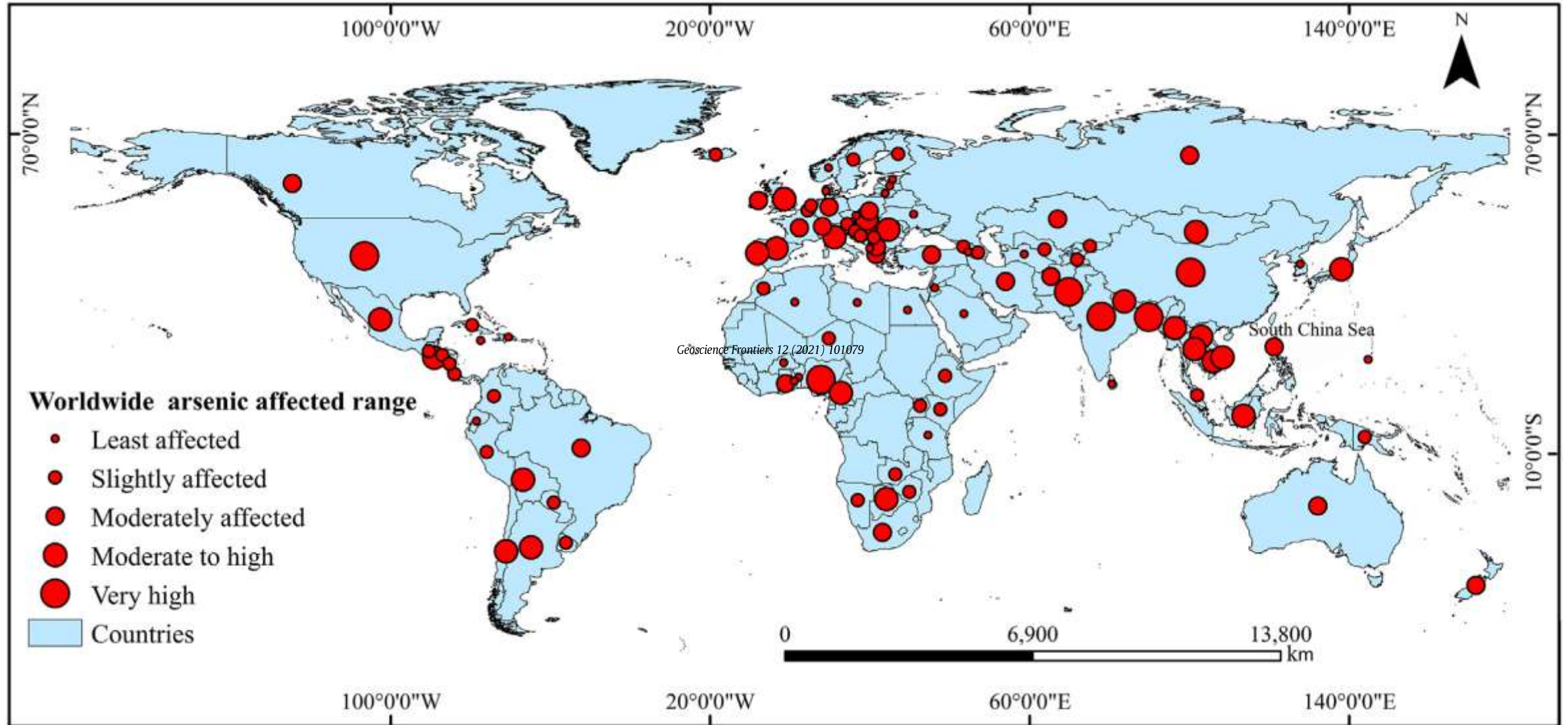
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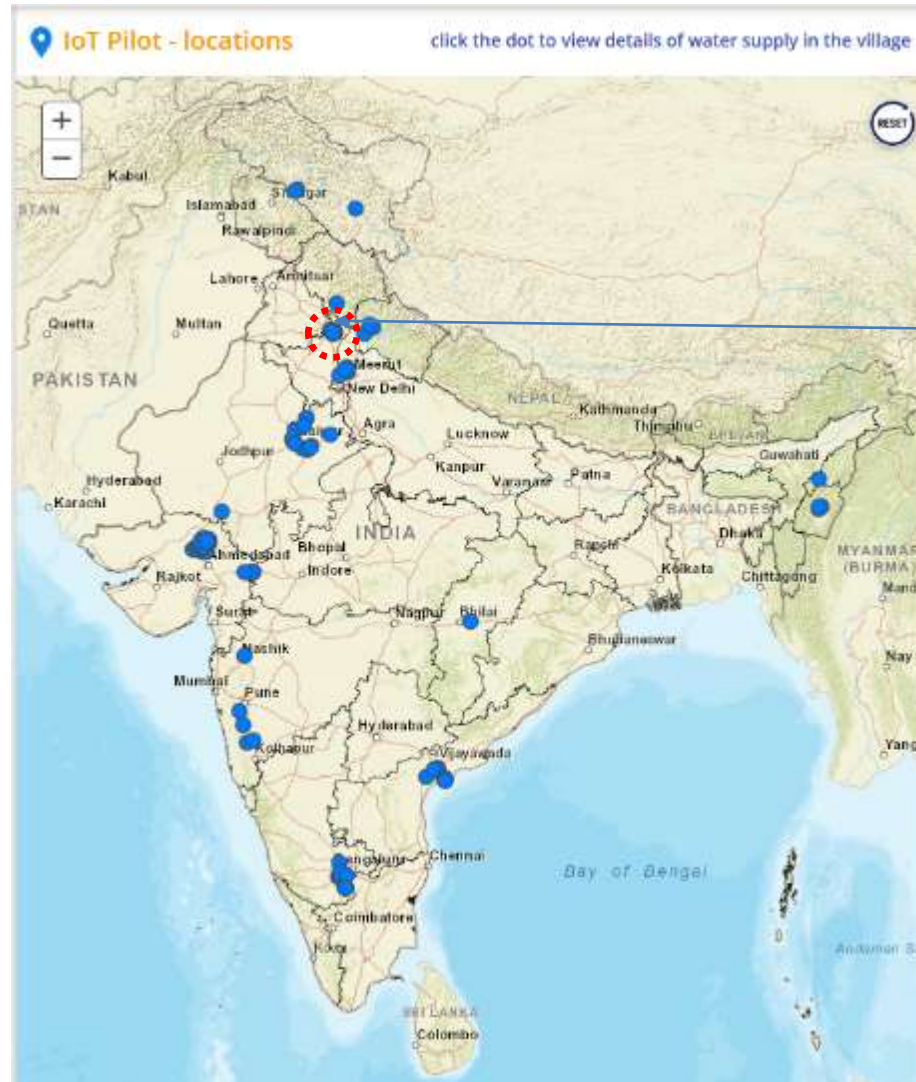


Arsenic poisoning across the world



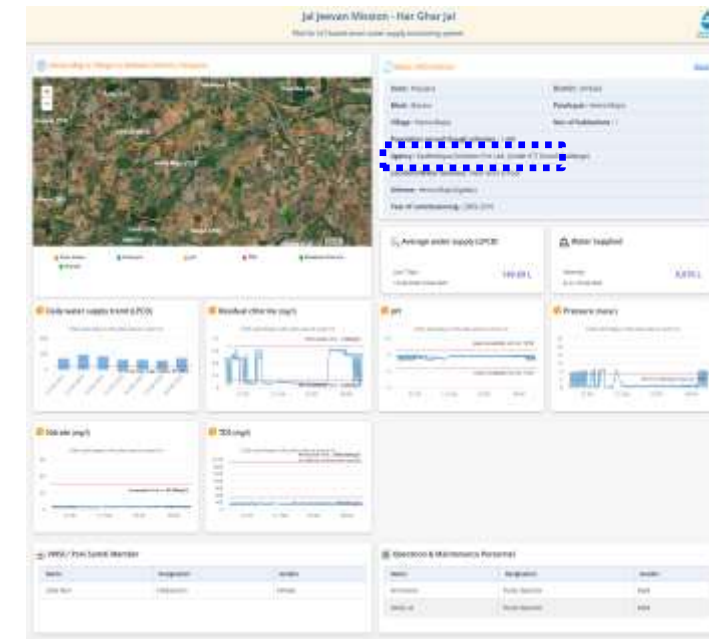


India's water is being monitored



IITM/IISc

Installations made by four companies





Can Water Microdroplets Make Soil?

A path to sustainable nanotechnology

Science

RESEARCH

NANOPARTICLES

Spontaneous weathering of natural minerals in charged water microdroplets forms nanomaterials

Et N. Spoorthe¹, Sayanika Ghosh², Palak Desai¹, Anil K. Singh¹, Umesh V. Waghmare², Bhagaji Prasad^{1,3*}

In this work, we show that particles of common minerals break down spontaneously to form nanoparticles in charged water microdroplets within milliseconds. Via transformation of natural minerals like quartz and mica into 5- to 10-nanometer particles when dispersed into aqueous microdroplets generated via electrospray. We deposited these droplets on a solid substrate, which allowed nanoparticles characterization. Via electron microscopy, we observed that particles undergo proton-induced etching, especially when reduced in size and exposed to an electric field. This leads to particle dissolution and the formation of silicate fragments, which we confirmed with mass spectrometry. This rapid weathering process may be important for soil formation given the prevalence of charged aerosols in the atmosphere.

Natural minerals of different sizes and compositions, such as quartz and mica, are known to be present in the atmosphere. These particles can be dispersed into aqueous microdroplets generated via electrospray. We deposited these droplets on a solid substrate, which allowed nanoparticles characterization. Via electron microscopy, we observed that particles undergo proton-induced etching, especially when reduced in size and exposed to an electric field. This leads to particle dissolution and the formation of silicate fragments, which we confirmed with mass spectrometry. This rapid weathering process may be important for soil formation given the prevalence of charged aerosols in the atmosphere.

For our experiments, we prepared different-sized particles of natural quartz (SiO₂) and mica (2H-mica) by dispersing them into charged water microdroplets (Fig. 1A and B). We generated these droplets via electrospray, which involves spraying a liquid through a narrow nozzle at high voltage, creating a fine mist of charged droplets.

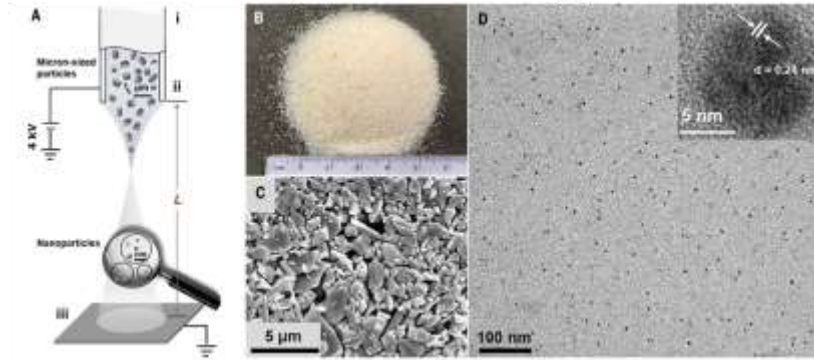
After the droplets were deposited on a solid substrate, we observed that the particles underwent a rapid weathering process. This was evident from the change in the morphology of the particles, which became smaller and more irregular in shape. We used scanning electron microscopy (SEM) to study the morphology of the particles before and after the weathering process. The SEM images showed that the particles were significantly smaller and more irregular in shape after the weathering process (Fig. 2C). This indicates that the particles underwent a rapid weathering process, which is consistent with the formation of nanomaterials.

Initial SEM images of the particles showed a smooth surface. However, after the weathering process, the particles showed a rough surface, which is characteristic of nanomaterials. We also used transmission electron microscopy (TEM) to study the morphology of the particles. The TEM images showed that the particles were significantly smaller and more irregular in shape after the weathering process (Fig. 3D). This indicates that the particles underwent a rapid weathering process, which is consistent with the formation of nanomaterials.

To understand the mechanism of the weathering process, we performed molecular dynamics (MD) simulations. The MD simulations showed that the particles underwent a rapid weathering process, which is consistent with the formation of nanomaterials. The MD simulations also showed that the particles were significantly smaller and more irregular in shape after the weathering process, which is consistent with the formation of nanomaterials.

Department of Chemistry, Indian Institute of Technology, Mumbai, India 400075, India. ²Theoretical Sciences Unit, Jawahar Institute for Advanced Scientific Research, Bangalore 560029, India. ³International Centre for Green Valley, IT Madras Research Park, Chennai 600160, India. *Corresponding author. Email: prasad@iitb.ac.in

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A scale of 1000

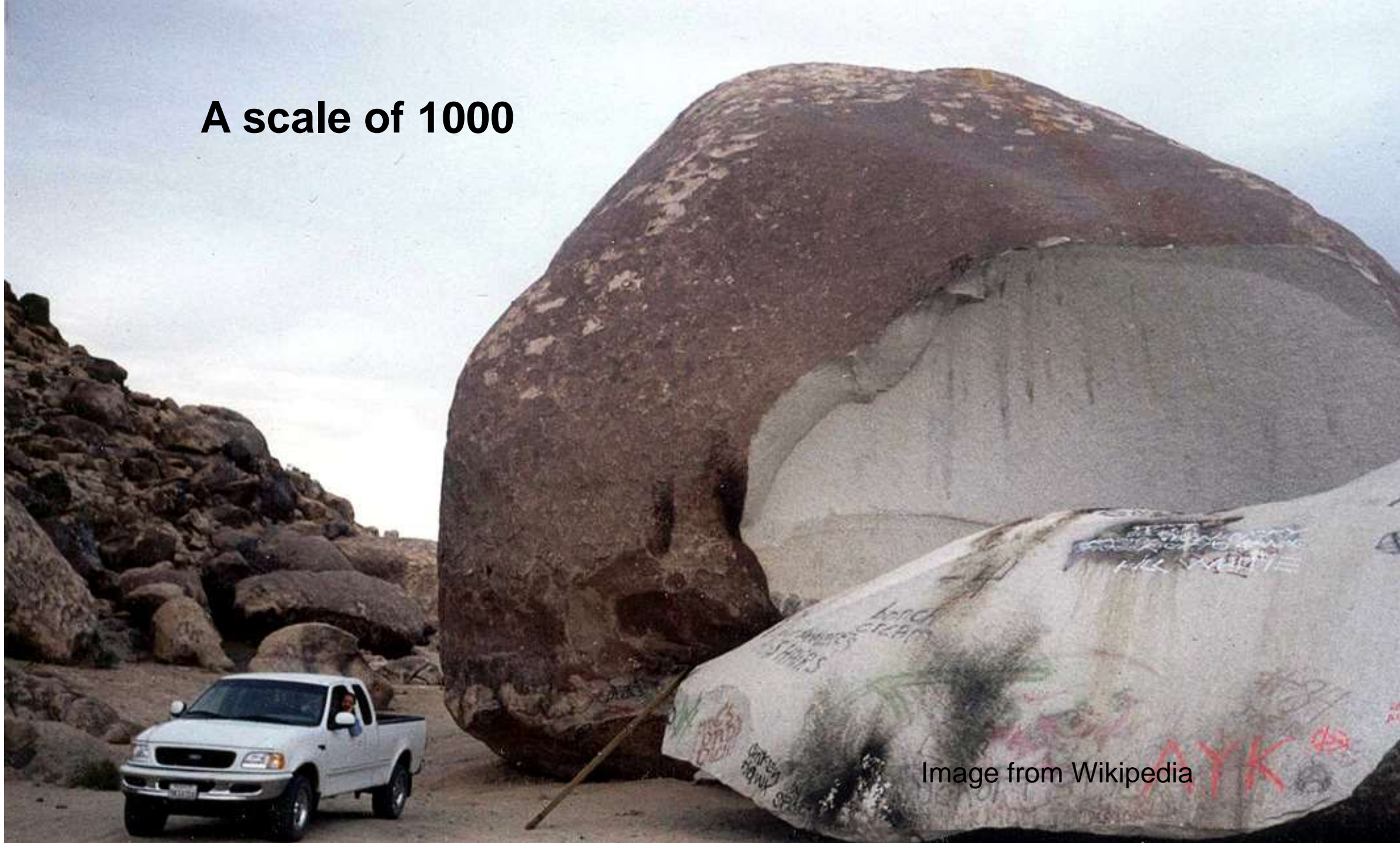
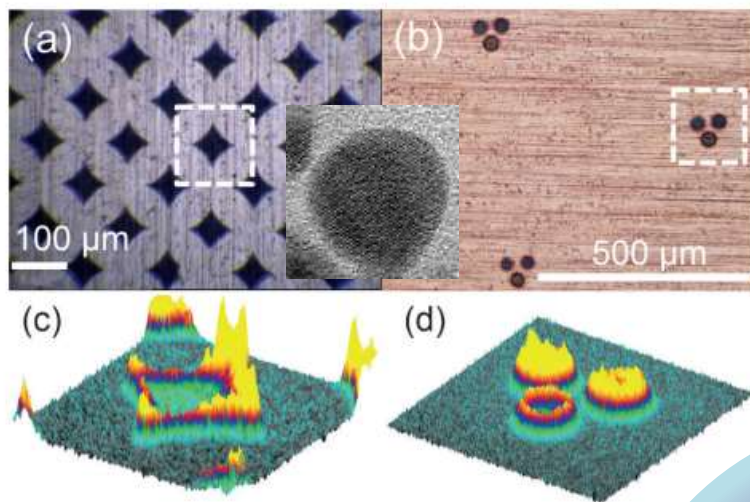
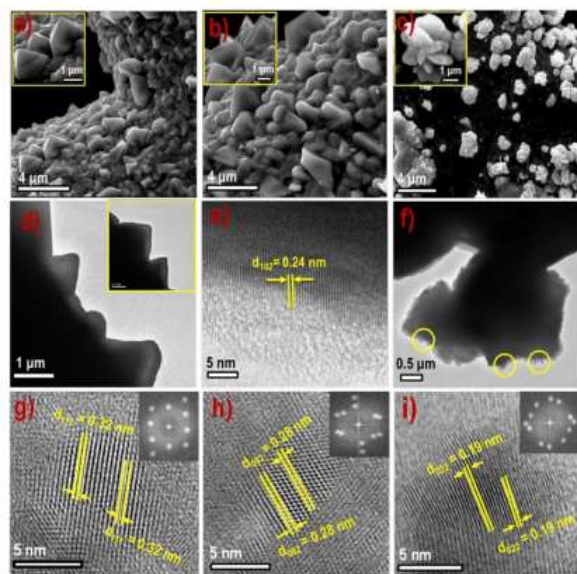
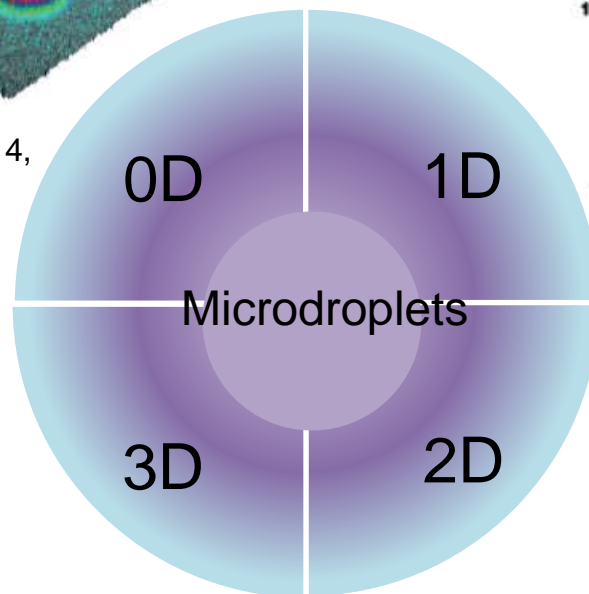


Image from Wikipedia

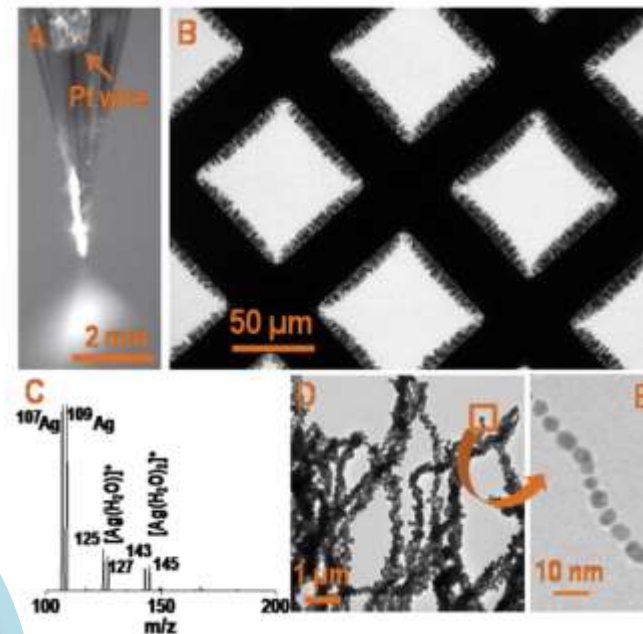
Functional Nanomaterials



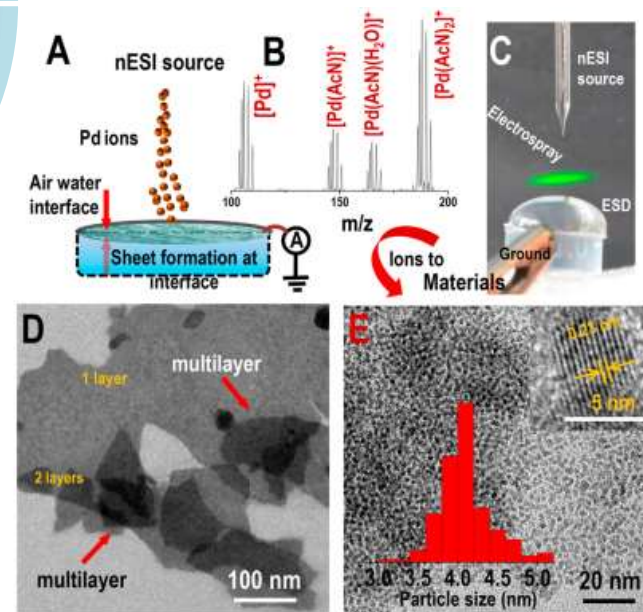
Anyin Li, et. al., *Angew. Chem. Int. Ed.* 2014, 53, 12528–12531.



Arijit Jana et. al., *J. Mater. Chem. A*, 2019, 7, 6387–6394.



Depanjan Sarkar et. al., *Adv. Mater.* 2016, 28, 2223–2228.



Depanjan Sarkar, et. al., *J. Phys. Chem. C* 2018, 122, 17777–17783.

Chemical Science

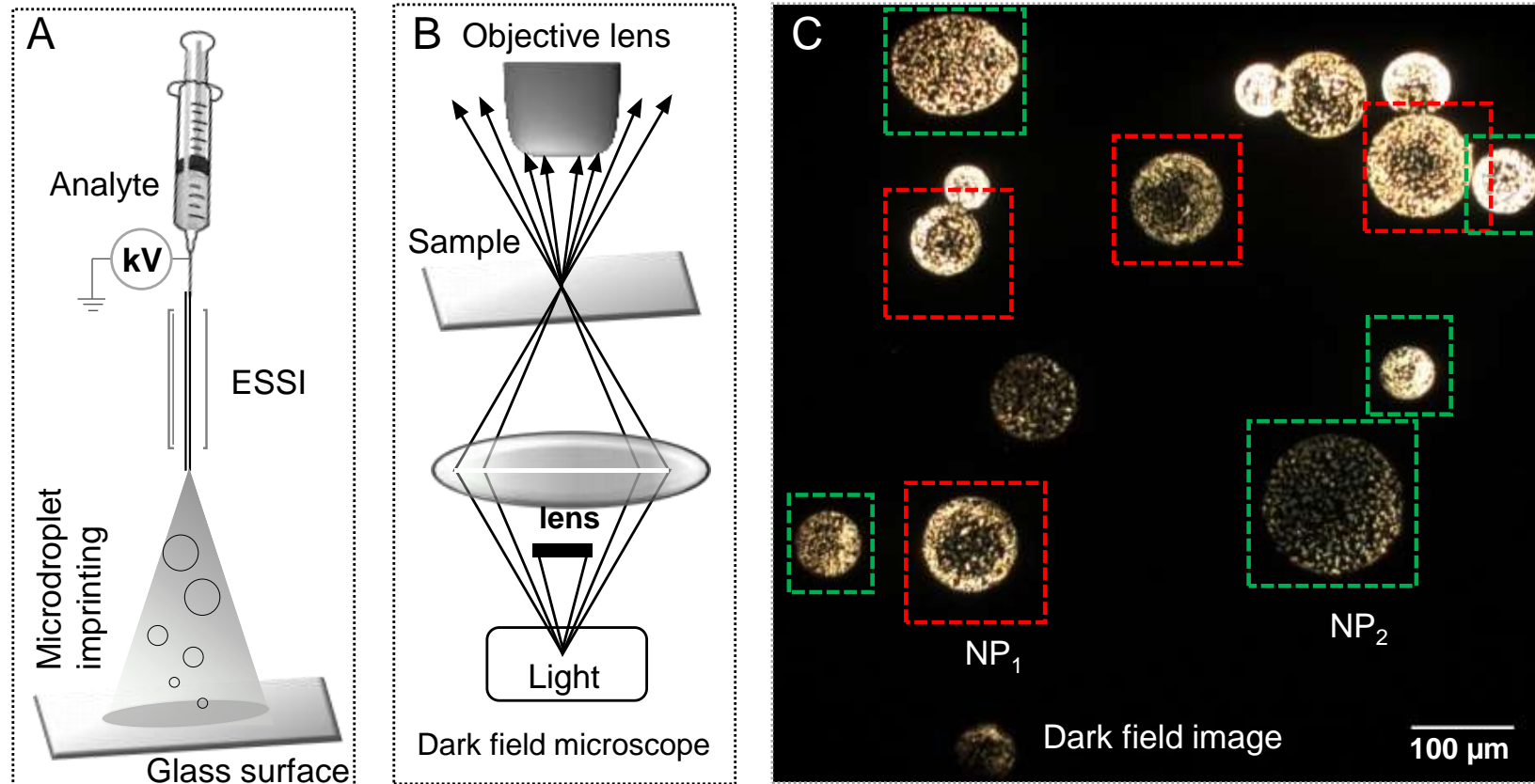
Volume 13
Number 45
7 December 2022
Pages 13251–13634

rsc.li/chemical-science



ISSN 2041-6539

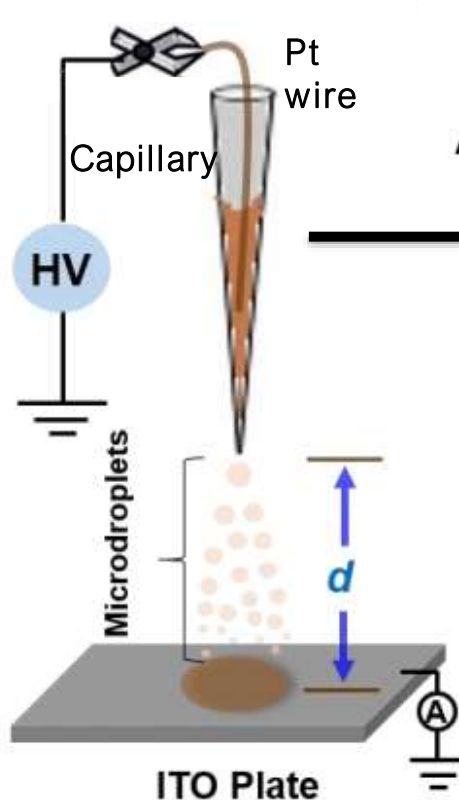
Understanding Microdroplets



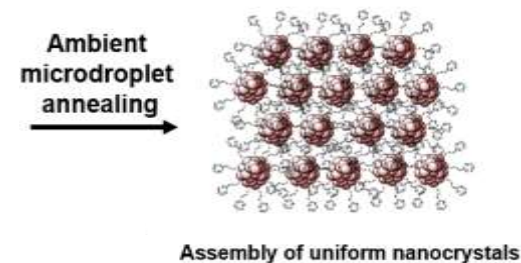
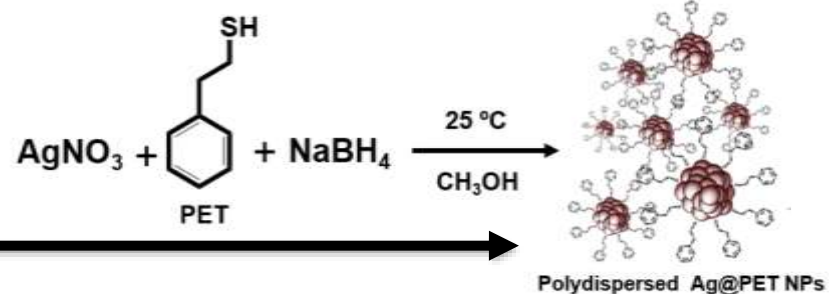
Transformation of Materials in Microdroplets

Ambient Microdroplet Annealing of Nanoparticles

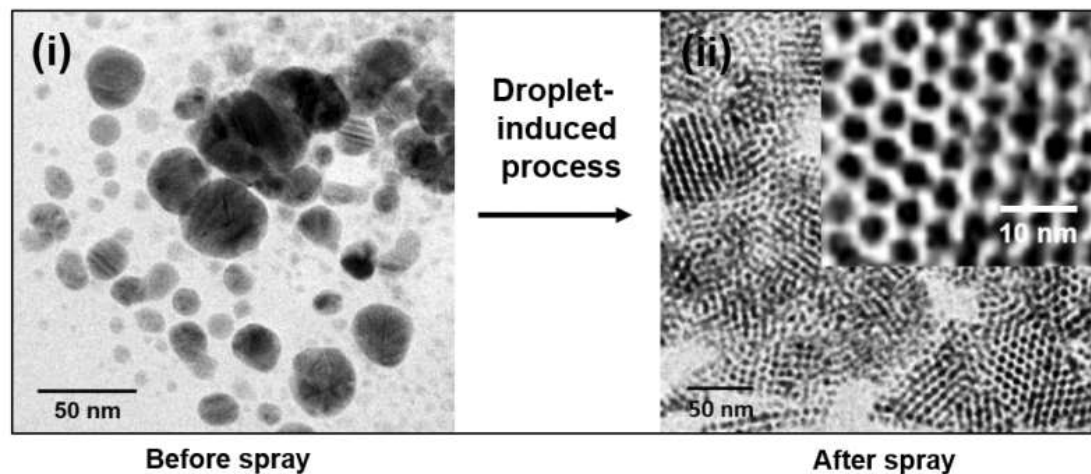
Experimental set-up



Synthesis of polydisperse NPs



Transformation process





Thanks to ChatGPT

Weathering in Nature

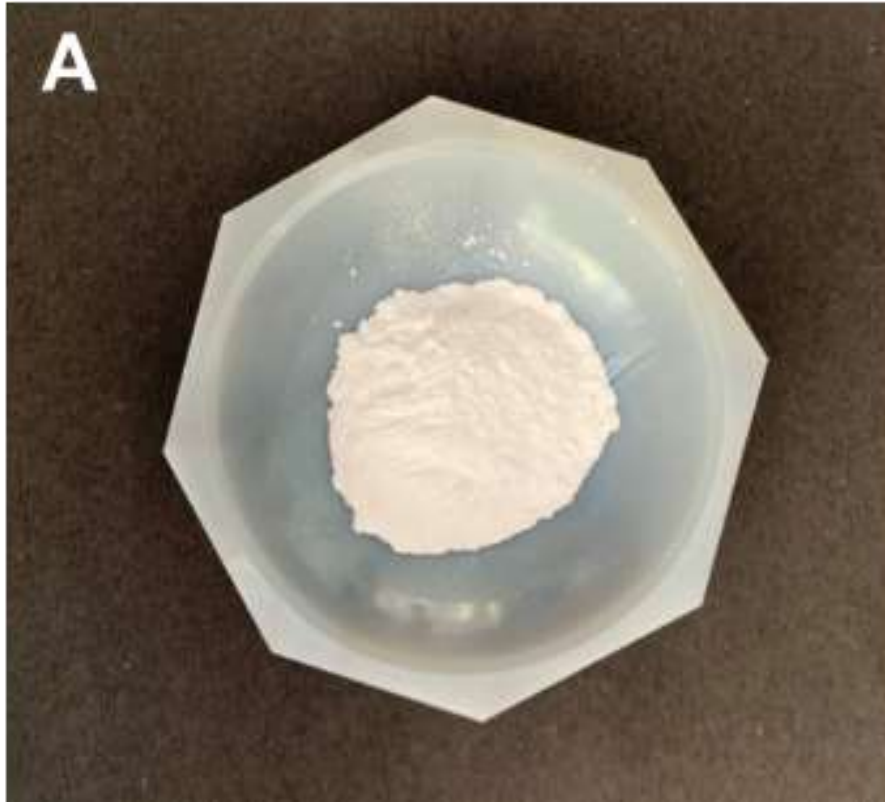


Sand, the Ubiquitous Material

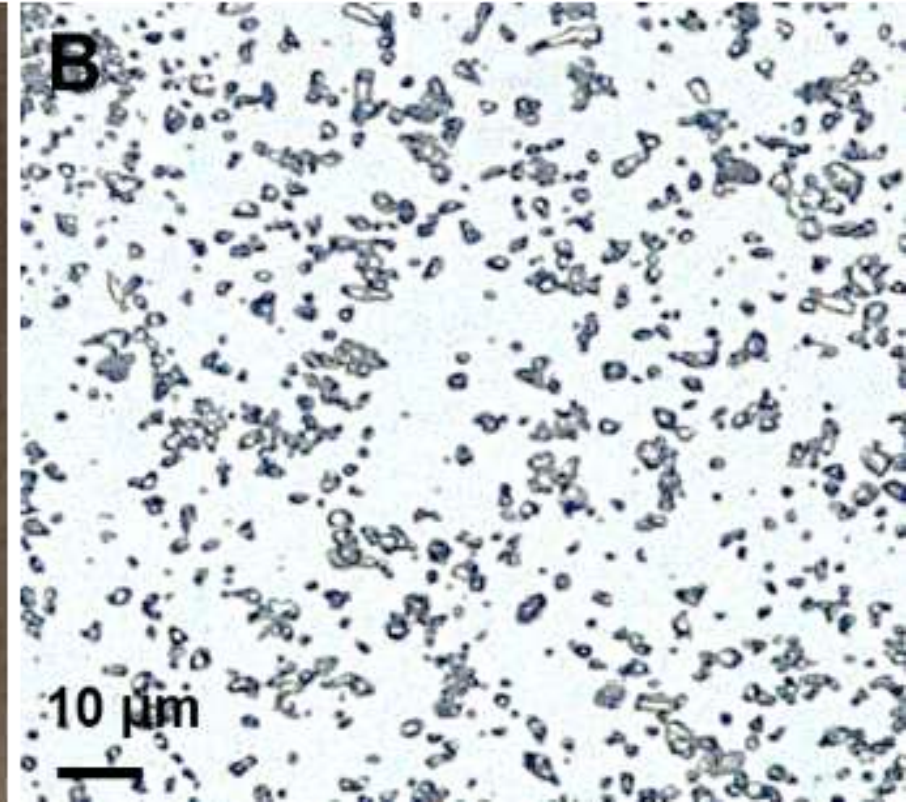


Images from Wikipedia



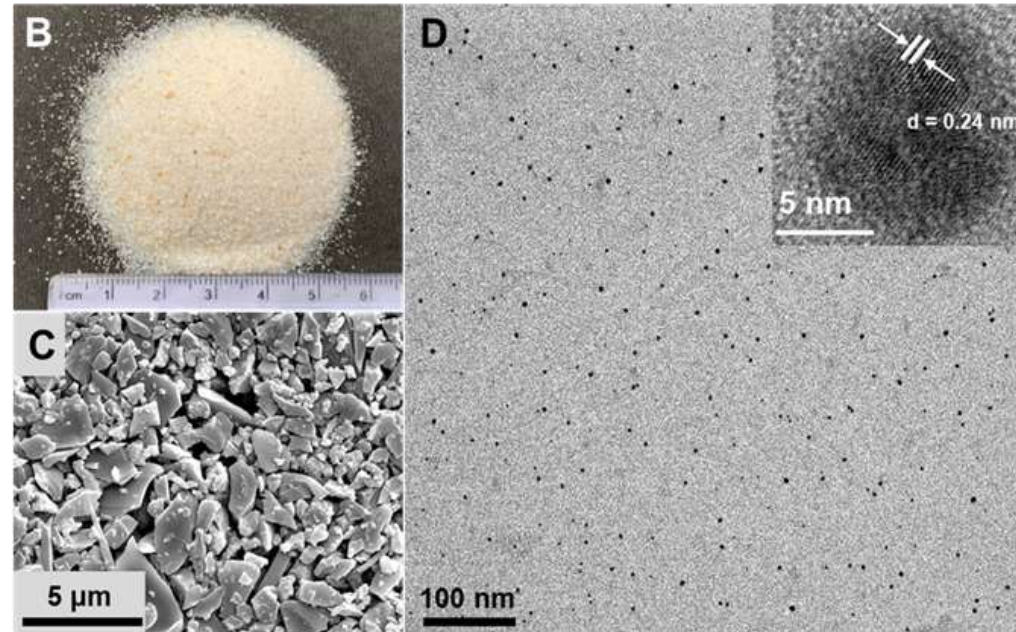
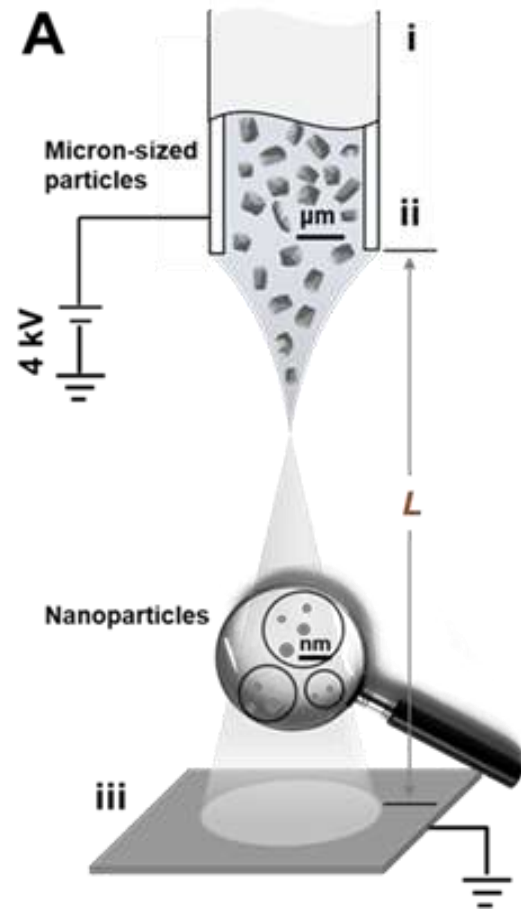


Ground silica

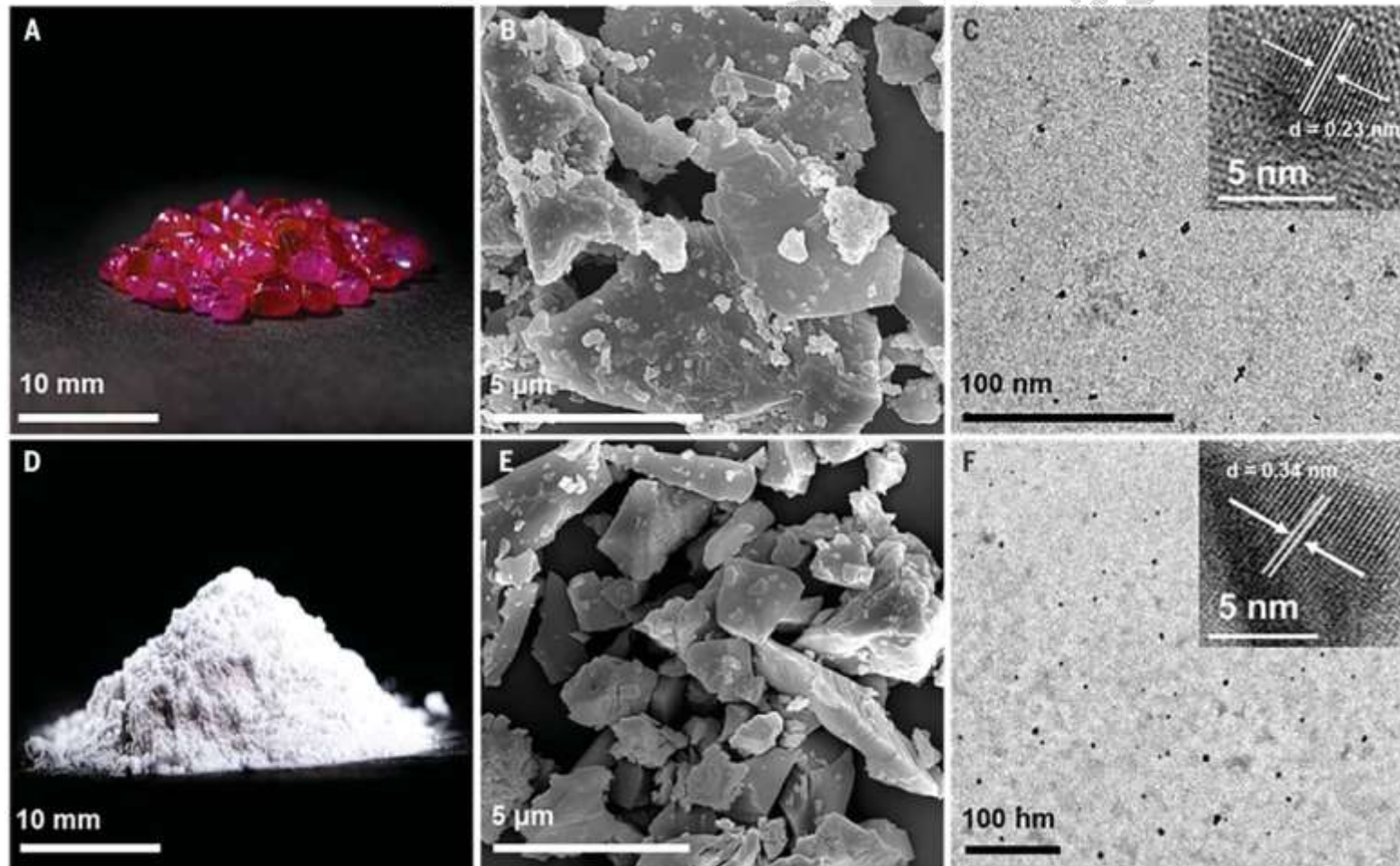


Optical image of silica

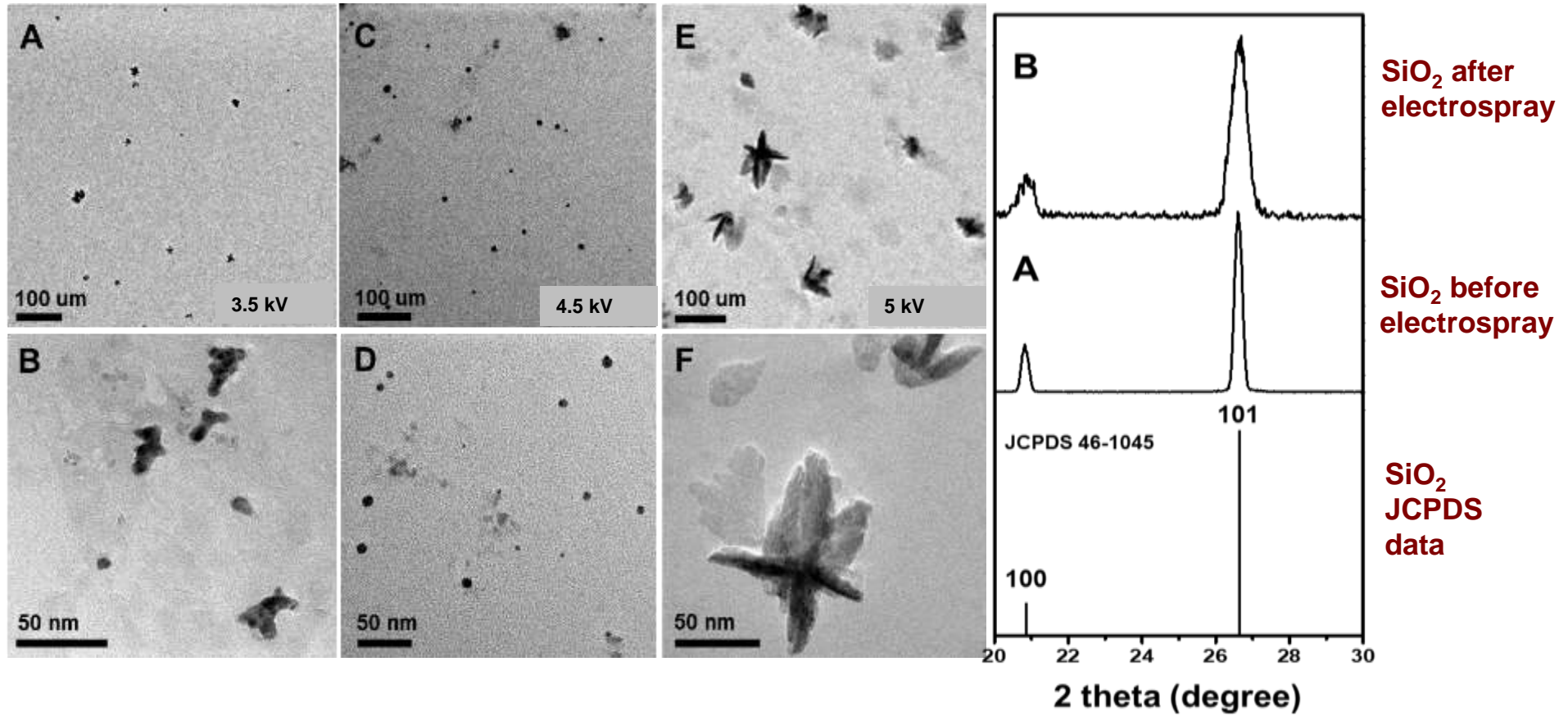
Weathering of Minerals in Microdroplets



Ruby, Fused Alumina

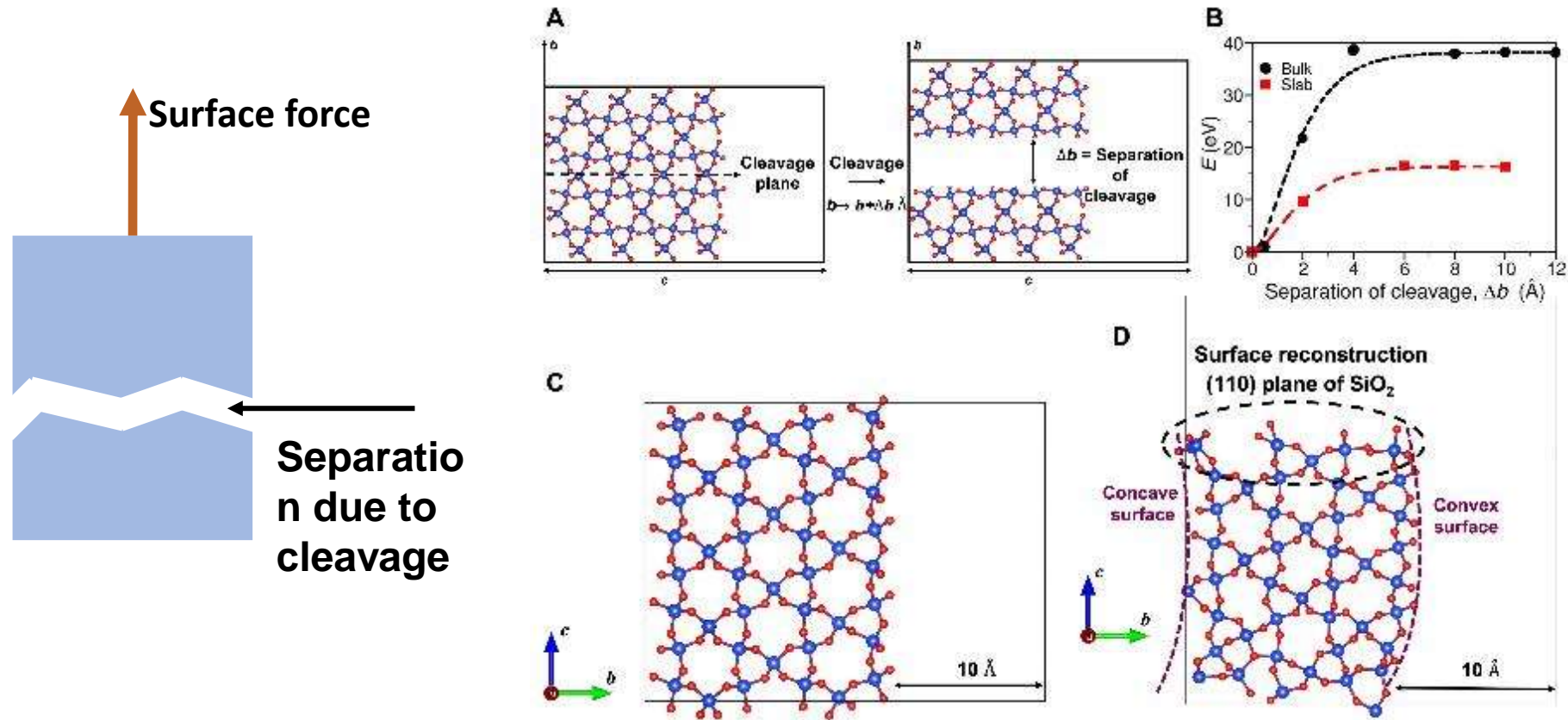


Fragmentation of Silica – Varying Conditions

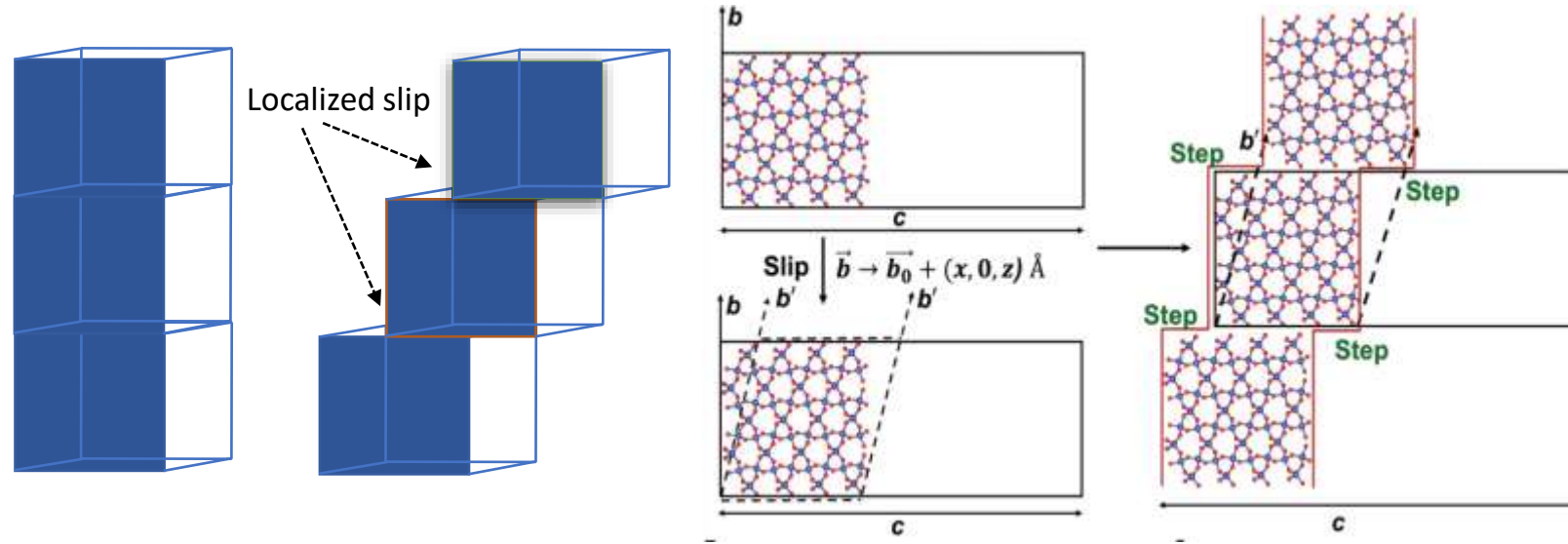


Mechanism: Cleavage

The process of cleavage and surface reconstruction visualized with first-principles simulations



Mechanism: Slip



This instability leads to the formation of a stacking fault on the (010) plane, achieved with slip localized at (010) plane

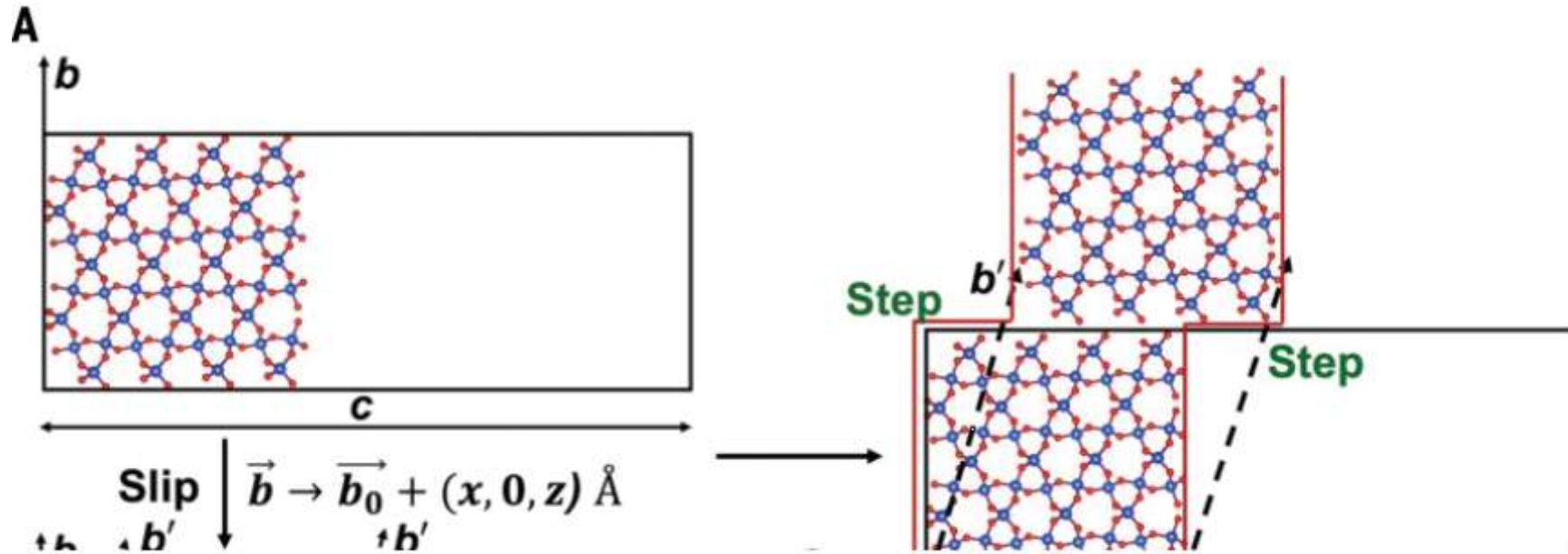
Stacking fault

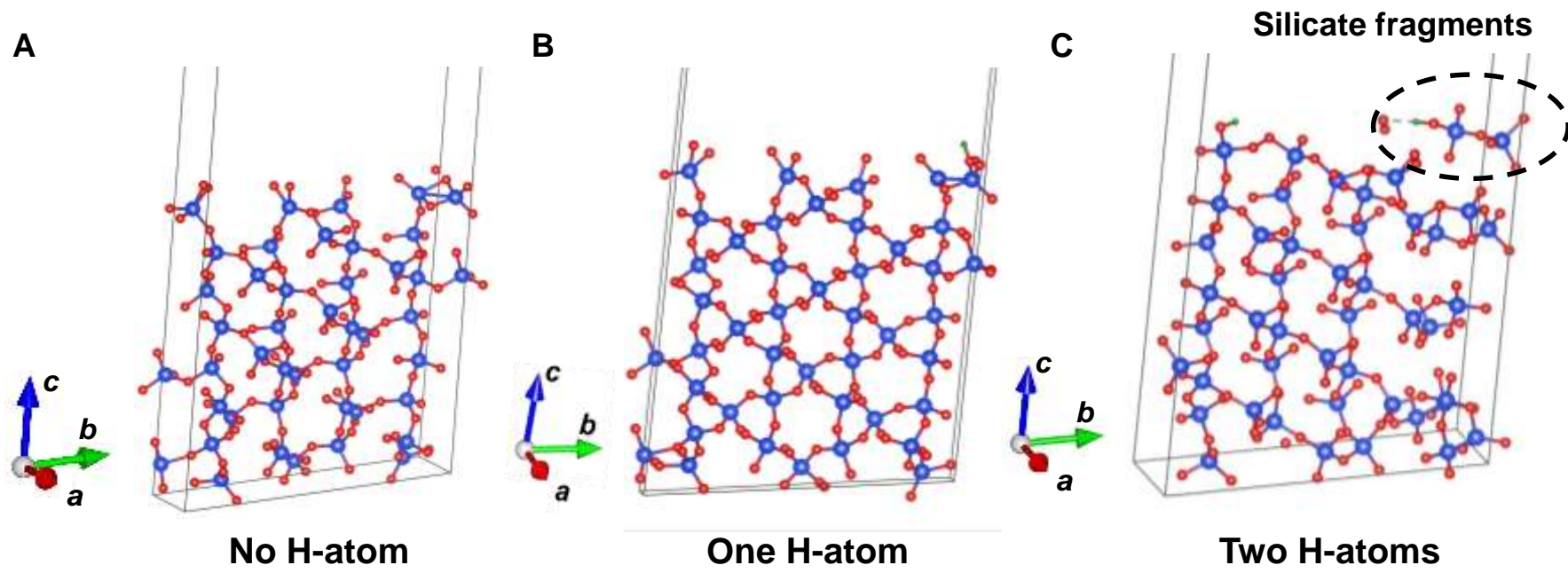
$$\vec{b} \rightarrow \vec{b}_0 + (x, 0, z)$$

$(x, z \in [0,1])$ - fractional coordinates

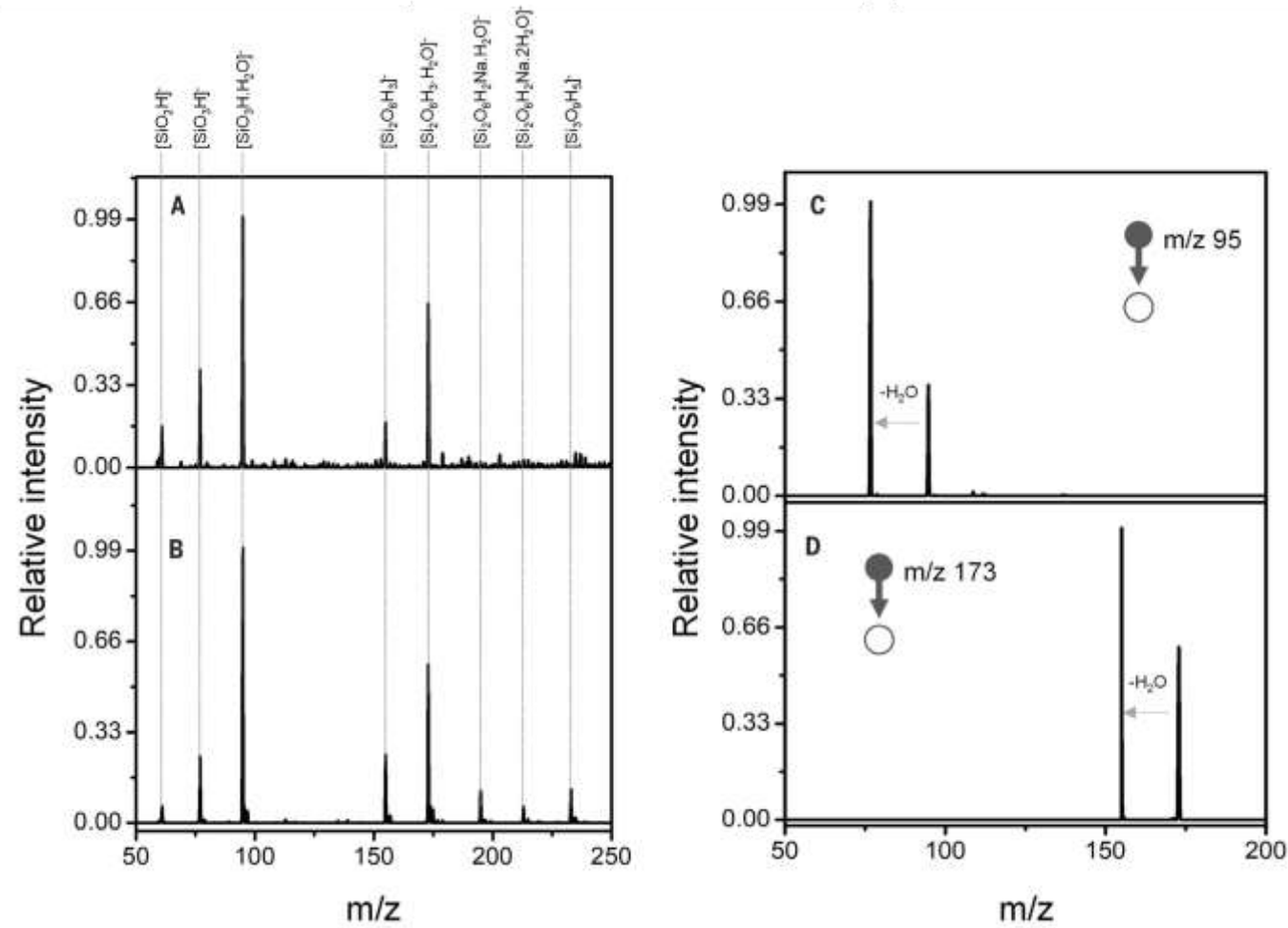
SFEs of (010) direction with (0, 0), (0, 0.5), (0.5, 0) and (0.5, 0.5) slip configurations on the (110) plane of SiO_2

SFE (J/m^2)	Slab					
	x	z	w/o H-atom	1 H-atom	2 H-atoms	E
	0.0	0.0	0	0	0	0
	0.5	0.5	-1.21	-0.93	-0.88	-1.20
	0.5	0.0	1.20	1.18	0.90	1.12
	0.0	0.5	-0.07	0.89	-0.83	-0.09

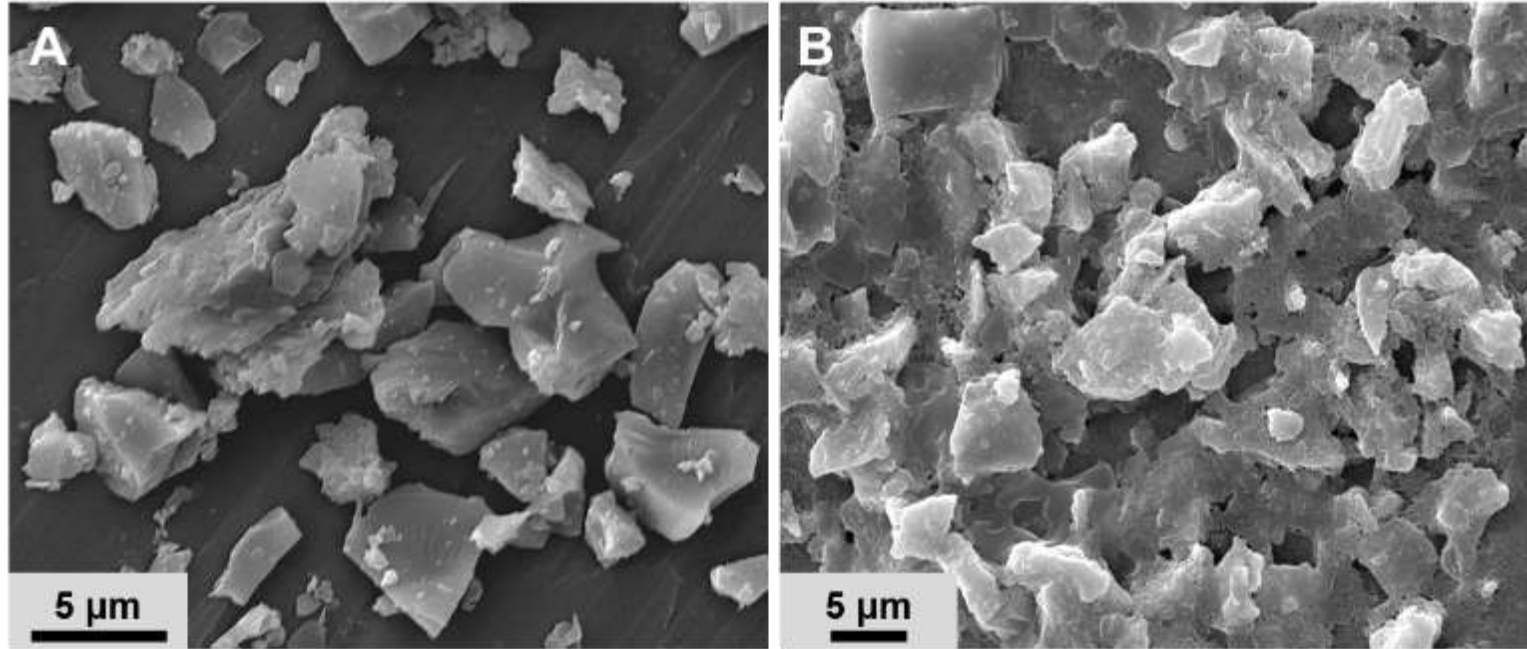




Mass Spectrometry of the Fragments

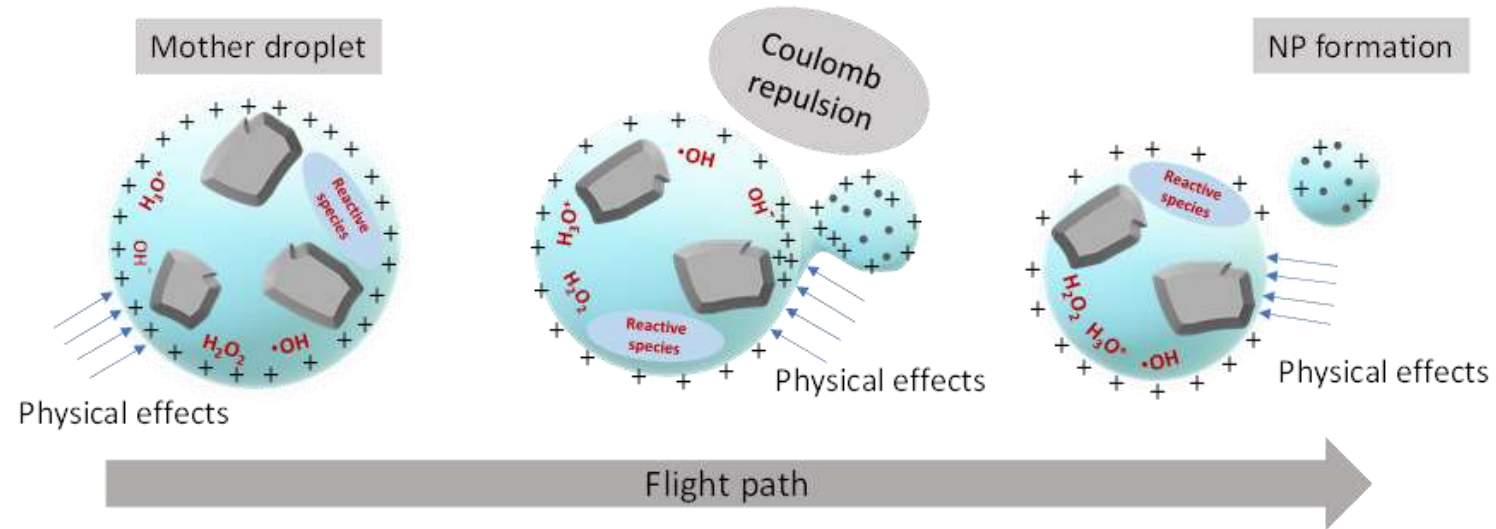


Effect of charged microdroplets on quartz



Increased surface roughness after the spray

Mechanism of nanoparticle formation



Rayleigh, On the
equilibrium of liquid
conducting masses
charged with electricity,
Philosophical Magazine,
1882

$$Q = 8\pi (\epsilon_0 \gamma R^3)^{1/2}$$

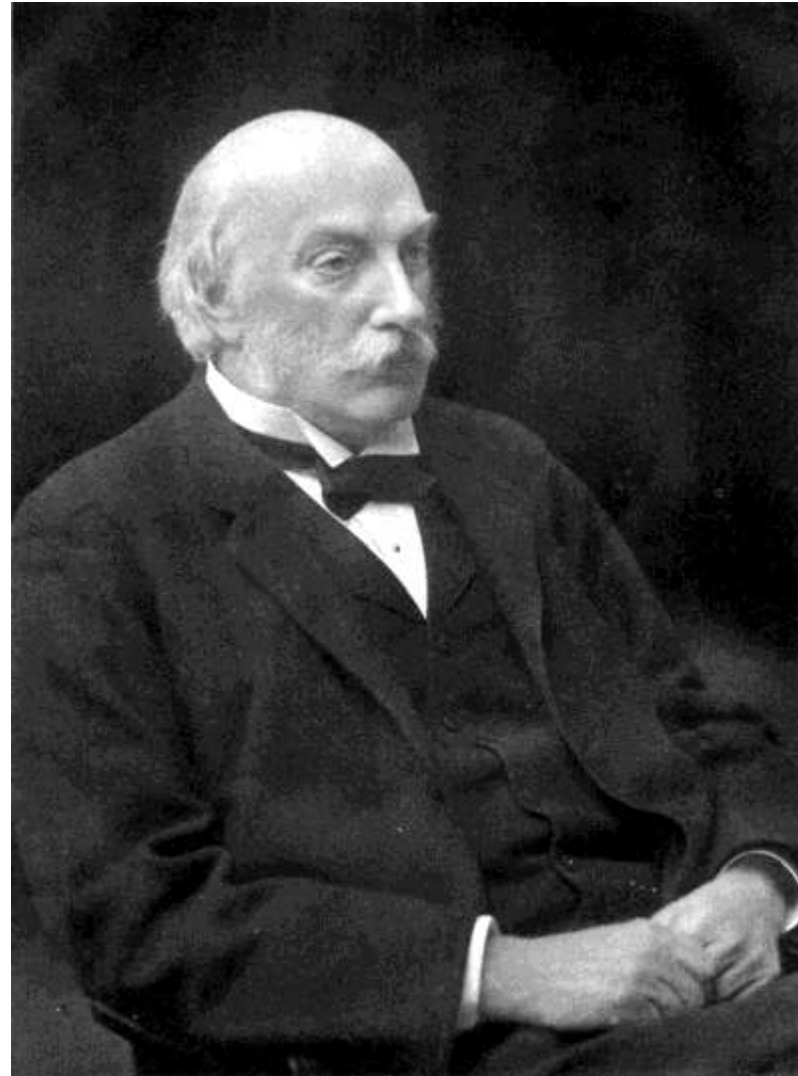
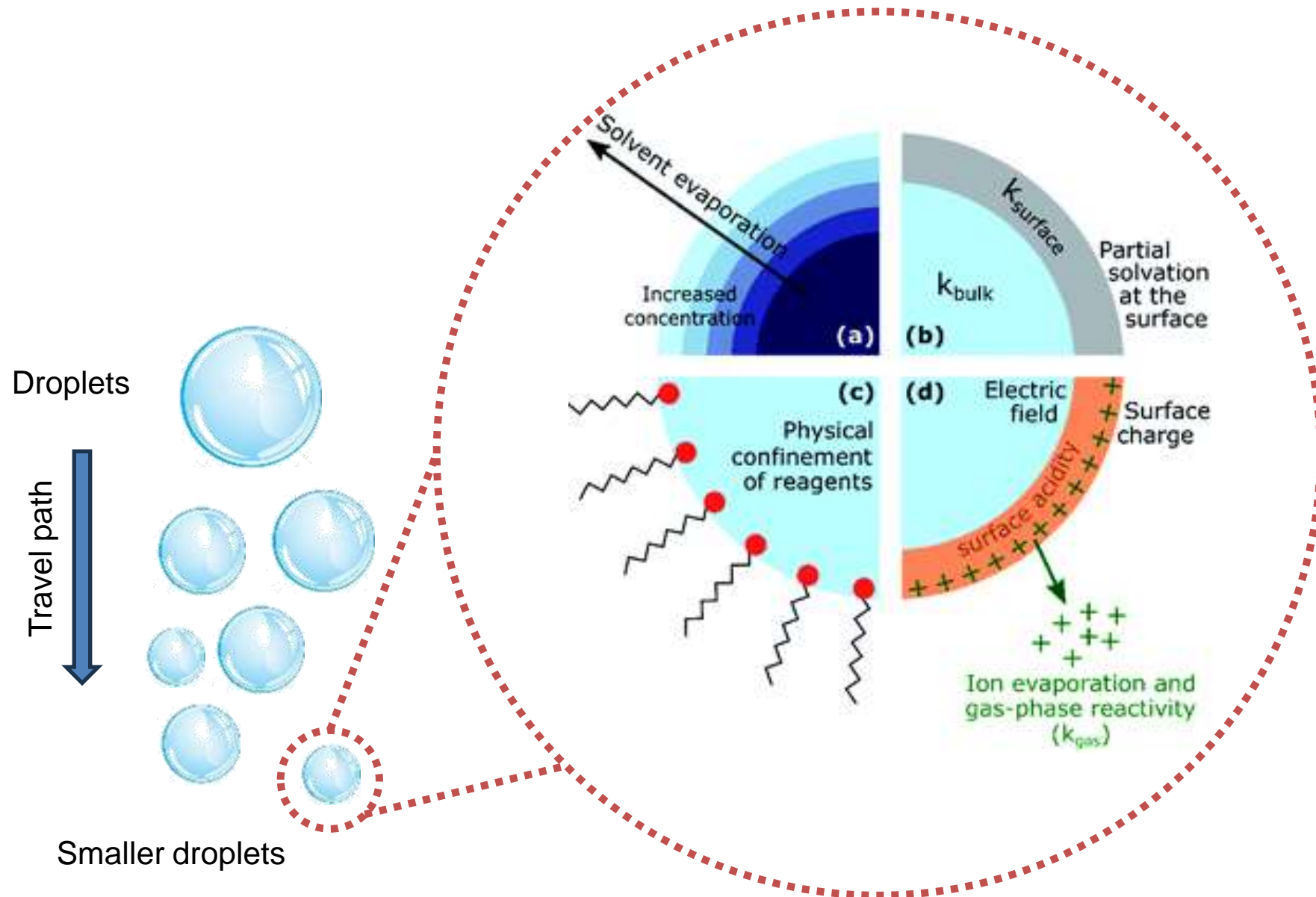


Image from Wikipedia

Understanding Microdroplets



PERSPECTIVES

CHEMISTRY

Breaking down microdroplet chemistry

Charged microdroplets accelerate mineral disintegration

By R. Graham Cooks and Dylan T. Holden

Charged microdroplets are commonly observed in clouds, sea spray, and other natural aerosols. The chemistry that occurs at the air-water interface of these droplets is often distinct from what is observed in bulk solution, which is of considerable interest because chemical reactions can be accelerated at this boundary (1, 2). This may have implications for environmental processes such as the weathering of rocks, which contributes to soil formation. On page 1012 of this issue, Spoorthi *et al.* (3) report that micrometer-scale mineral particles can rapidly break down into nanoparticles when in charged aqueous microdroplets (see the figure). This points to a potential role for atmospheric water droplets in the natural disintegration of minerals.

To examine material degradation, Spoorthi *et al.* borrowed methodology used to accelerate bond-forming chemical reactions. By spraying an aqueous suspension of microparticles of natural minerals, the authors produced nanoparticles of minerals in high yield. Specifically, Spoorthi *et al.* used an electrospray device to emit a jet of liquid droplets (by applying high voltage) containing mineral particles of natural quartz, ruby, or synthetic alumina that ranged in size from 1 to 5 μm in diameter. The authors observed the production of nanoparticles that were 5 to 10 nm in diameter. Moreover, the fragmentation occurred in approximately 10 ms.

Such material degradation and chemical synthesis experiments are united by the extremes of chemical reactivity that occur at the air-water interface, where reagents are partially solvated (4). Whether formed through nebulization, splashing from a surface, or other means, microdroplet populations will include droplets with nonzero net charges. The small radius of curvature in a microdroplet produces a very strong electric field (5) that can support a double layer of electric charge at the air-water interface. The change in geometry (radius of curvature)

converts a two-dimensional air-water interface with limited electric field into a sphere with an electric field of a strength approaching the order of chemical bond energies (3 to 4.5 eV/Å). Coulombic fission (the splitting of charged microdroplets due to excess charge overcoming the surface tension) and evaporative processes further increase the surface area, reduce the radius of curvature, and augment the surface electric field of the droplet.

The unusual chemical nature of the air-water interface results in much remarkable chemistry. For example, amino acids in water undergo dehydration to form peptides in this environment (6), whereas bulk water simply solvates amino acids. The superacidic interface activates amino acids and removes water to yield peptides. In addition to such acid-base reactions, redox chemistry results from the formation of strong oxidants and reductants from water at the interface. For example, a high hydronium ion (H_3O^+) concentration at the interface derived from fleetingly charged surface water molecules ($\text{H}_2\text{O}^+/\text{H}_2\text{O}^-$) coexists with oxidative species such as hydrogen peroxide (H_2O_2) and OH^\bullet . These redox species enable a variety of spontaneous chemical trans-

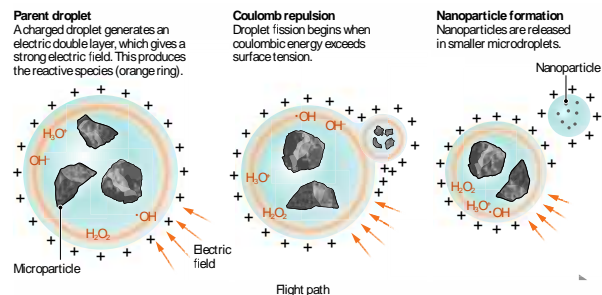
formations, including carbon-oxygen (C-O) bond cleavage in phosphonates, which yields the corresponding phosphonic acid (7), and in the Baeyer-Villiger oxidation of aryl ketones to give esters (8). These considerations thereby enable simultaneous acid-base and oxidation-reduction chemistry in a single population of droplets (7).

Through their study, Spoorthi *et al.* have added natural weathering to a list of processes in which accelerated interfacial microdroplet reactions play an important role. Other processes include those in the atmosphere, both natural and anthropogenic, the latter typified by pollution that involves nitrate photochemistry (9). A substantial number of accelerated catalyst-free microdroplet reactions form the basis for chemical syntheses that generate a variety of small molecules (10), including the facile and high-throughput functionalization of drugs. This latter approach can be scaled up so that microdroplet reactions produce substantial small-molecule products. Prebiotic chemistry, including peptide and nucleotide formation, is another process that is accelerated at the microdroplet air-water interface (11).

The millisecond timescale of quartz degradation reported by Spoorthi *et al.* matches the known microsecond-to-millisecond timescale for accelerated bond-formation and bond-cleavage chemical reactions in microdroplets (1). This reinforces the conclusion that the chemical basis for accelerated weathering lies in the powerful acidic and hydrolytic nature of the air-water interface. The authors further suggest a role for the superacid interface in inducing slippage at crystal plane boundaries in quartz and ruby fragmentation. Their simulations show that individual protons inserted into the slip configuration mineral

Micro-to-nano transitions in minerals at the air-water interface

Reactions that promote mineral disintegration are accelerated at the air-water interface of microdroplets. Key reactive species are the result of the effects of a high electric field at the surface of the water droplets.



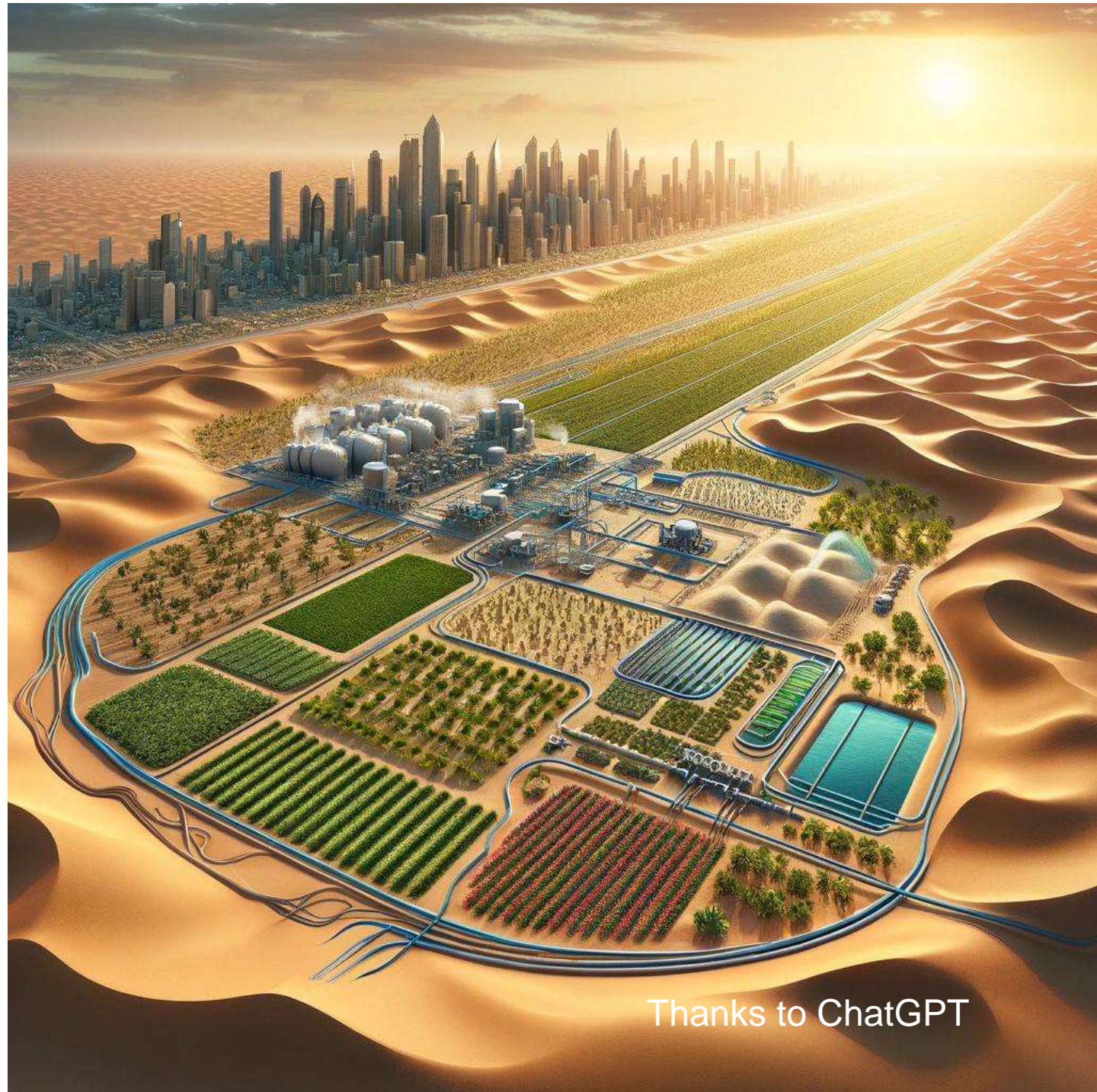
Department of Chemistry, Purdue University, West Lafayette, IN, USA. Email: cooks@purdue.edu



Thanks to ChatGPT

Vision

Make soil using
processed wastewater
and make deserts
bloom.

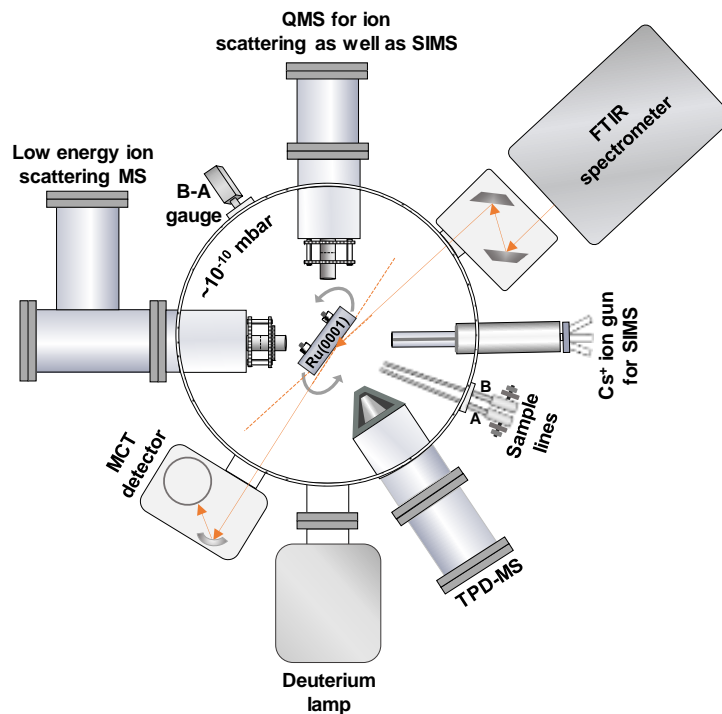
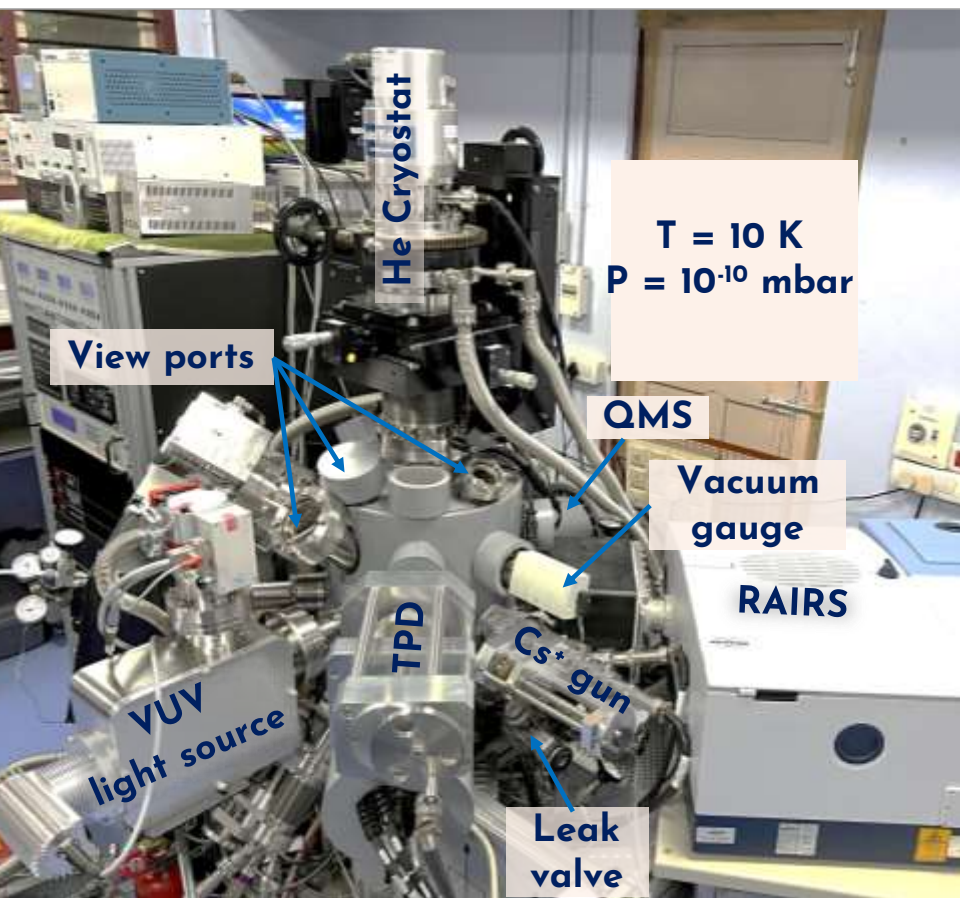


Thanks to ChatGPT

Can Clathrate Hydrates Exist in Space?

Exploring astrobiology

Instrumentation

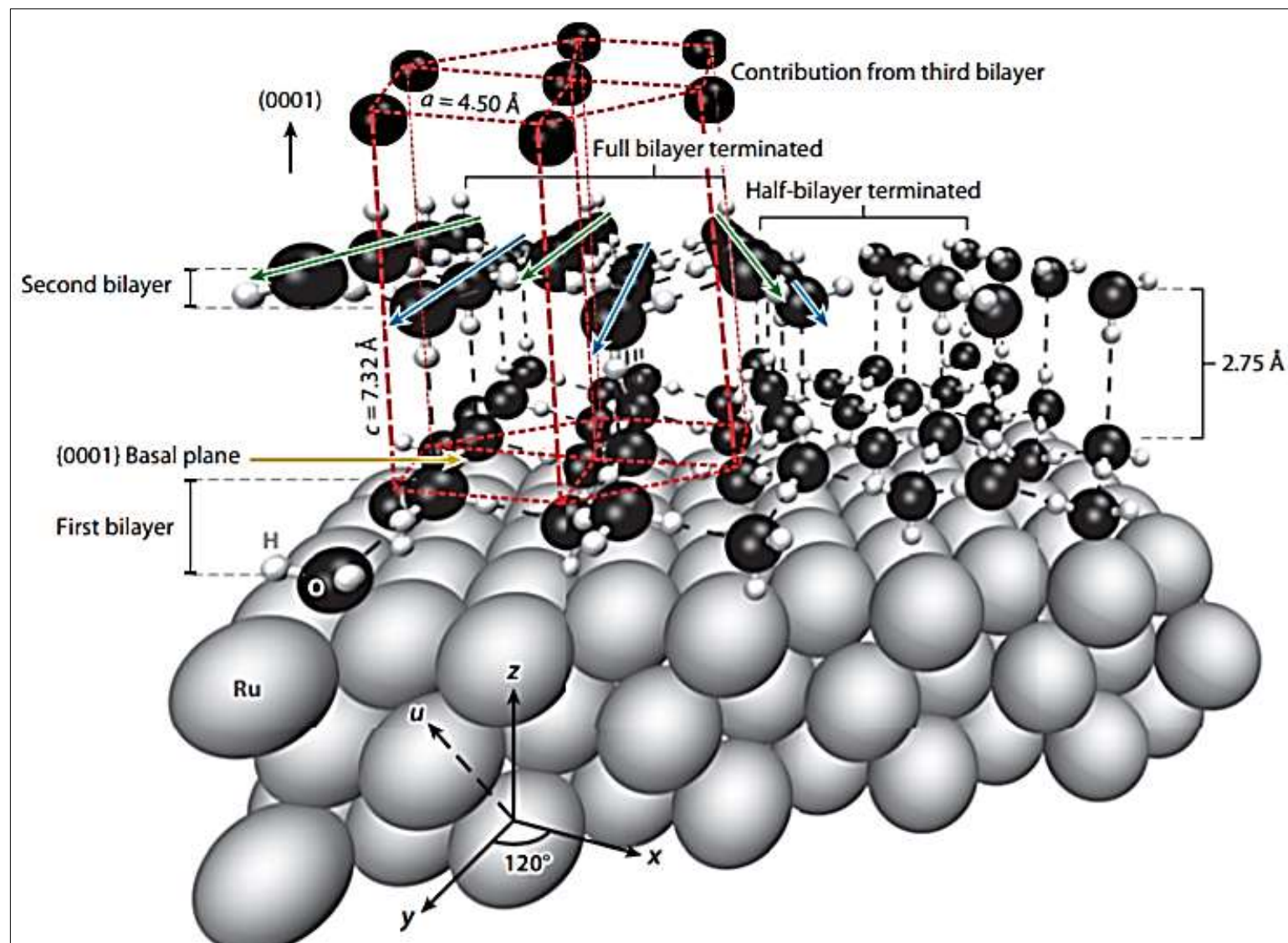


115-400 nm



Bag, S. et al., *Rev. Sci. Instrum.* **2014**, 85, 014103/1-014103/7

Viswakarma, G. et al., *J. Phys. Chem. Lett.*, **2023**, 14, 2823–2829



Formation and Transformation of Clathrate Hydrates under Interstellar Conditions

Jyotirmoy Ghosh, Gaurav Vishwakarma, Rajnish Kumar,* and Thalappil Pradeep*

Cite This: <https://doi.org/10.1021/acs.accounts.3c00317>

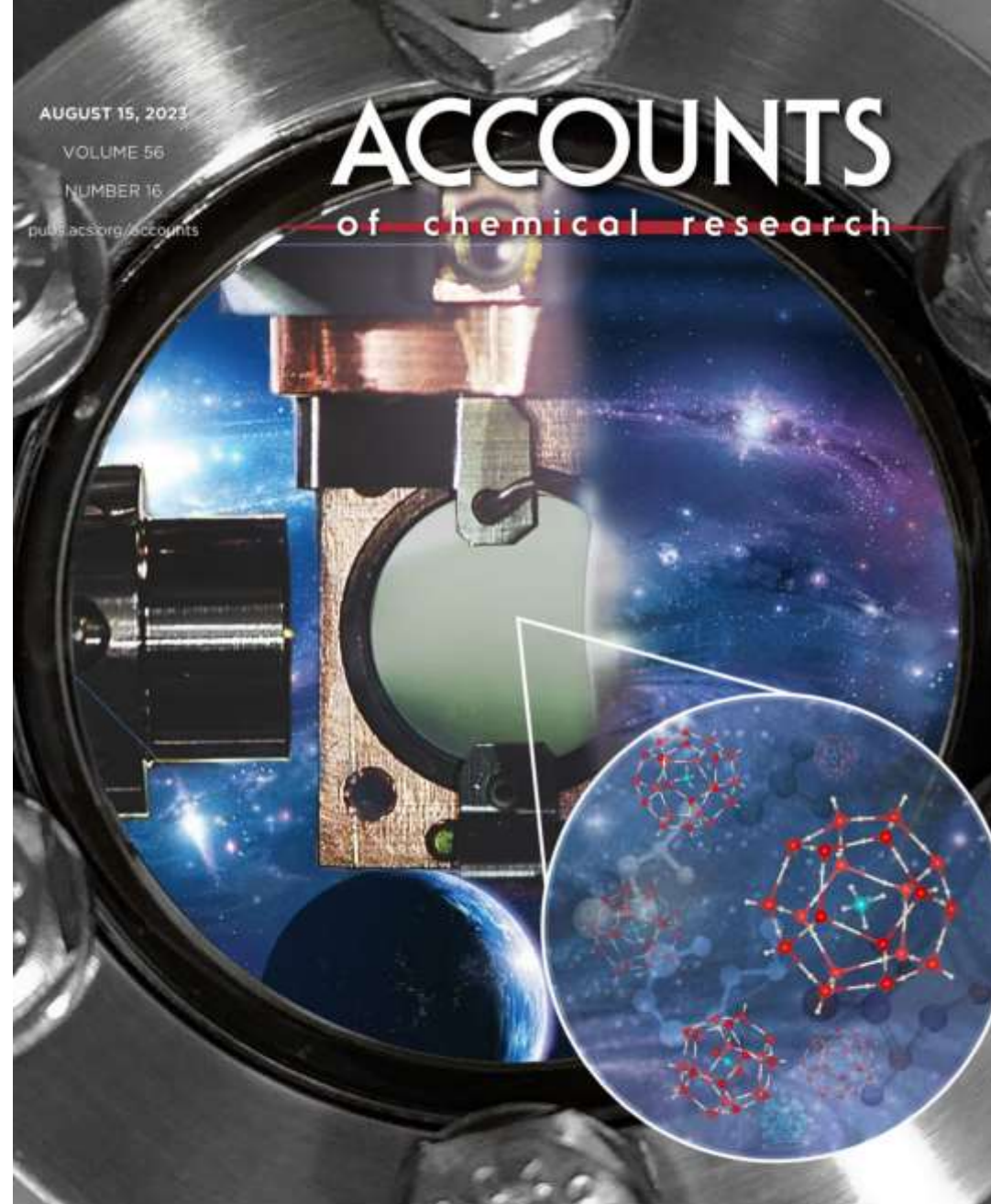
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AUGUST 15, 2023

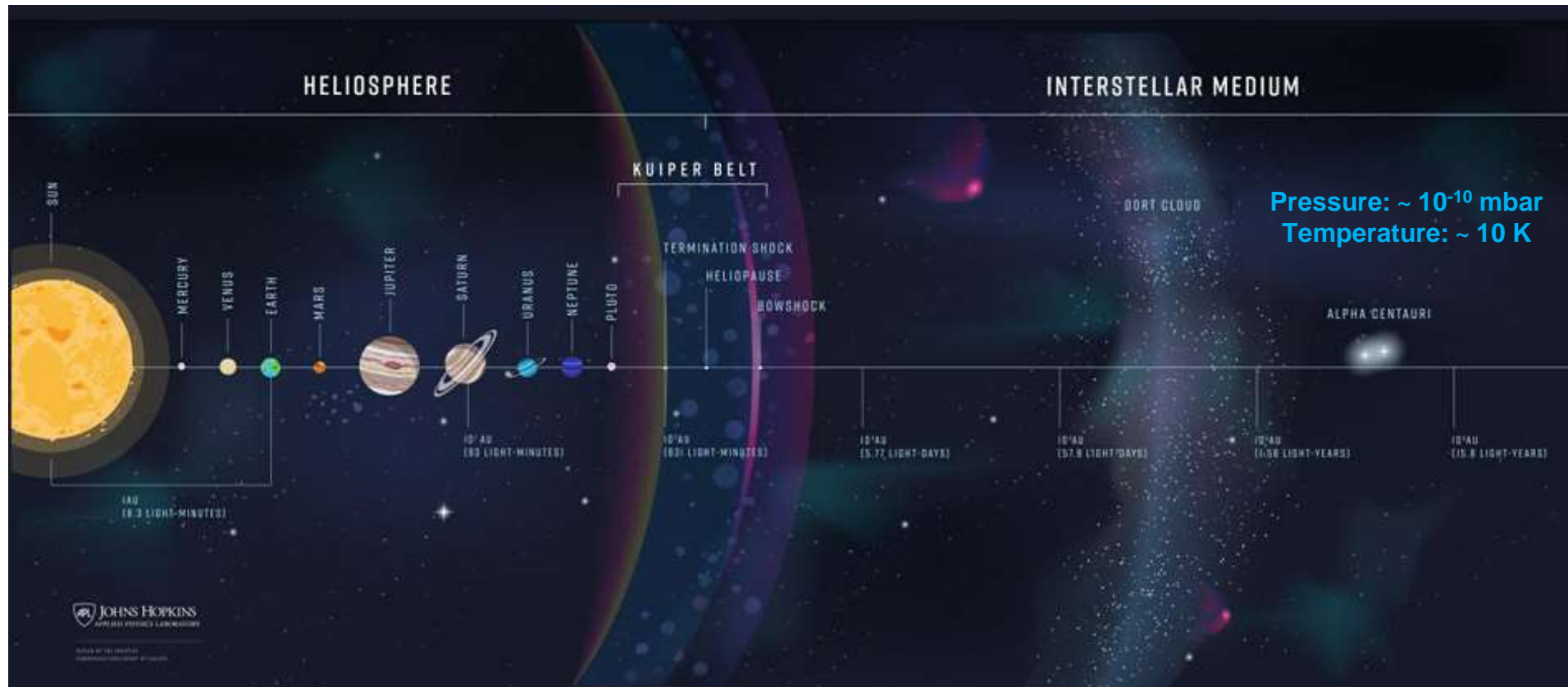
VOLUME 56

NUMBER 16

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Interstellar medium

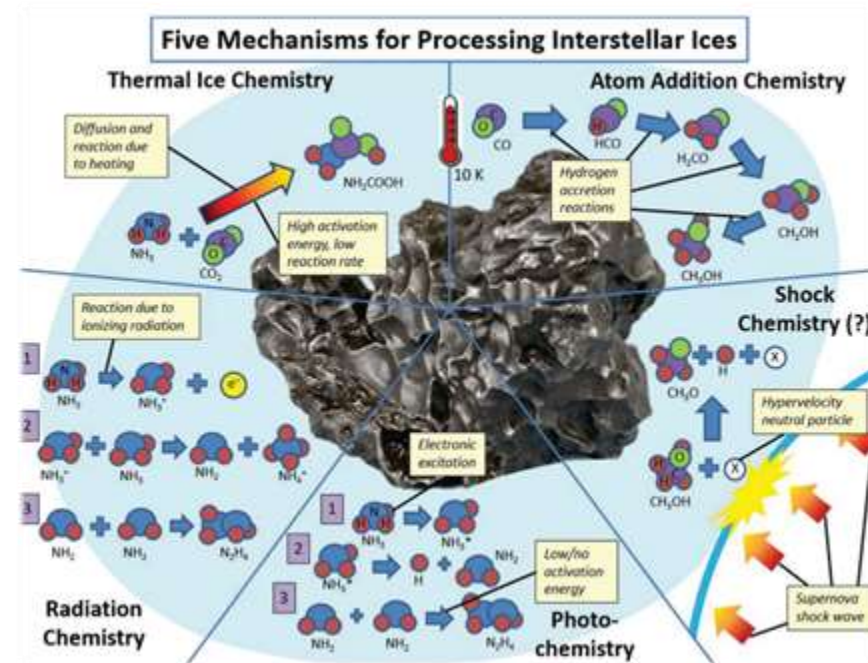
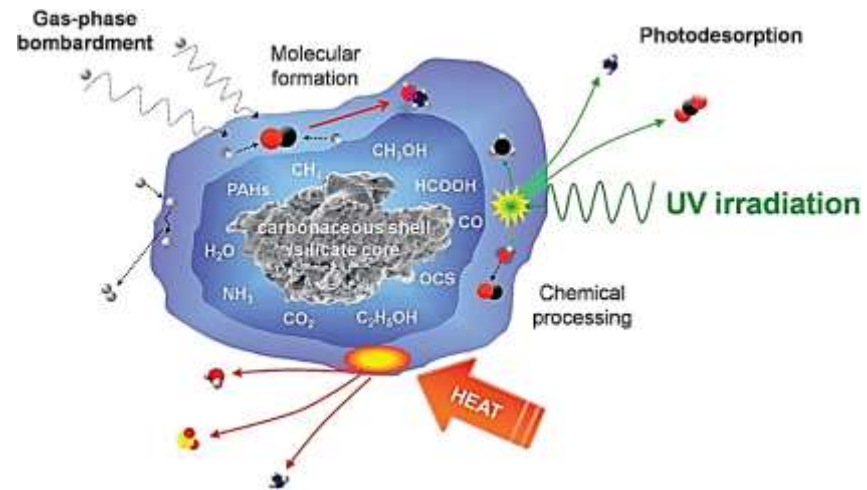


Diffuse clouds: $T \sim 100$ K, $n \sim 100$ molecules per cm^3

Dense clouds: $T \sim 10$ - 100 K, $n \sim 10^4$ - 10^8 molecules per cm^3

On Earth sea level: $T \sim 300$ K, $n \sim 3 \times 10^{19}$ molecules per cm^3

Interstellar ices



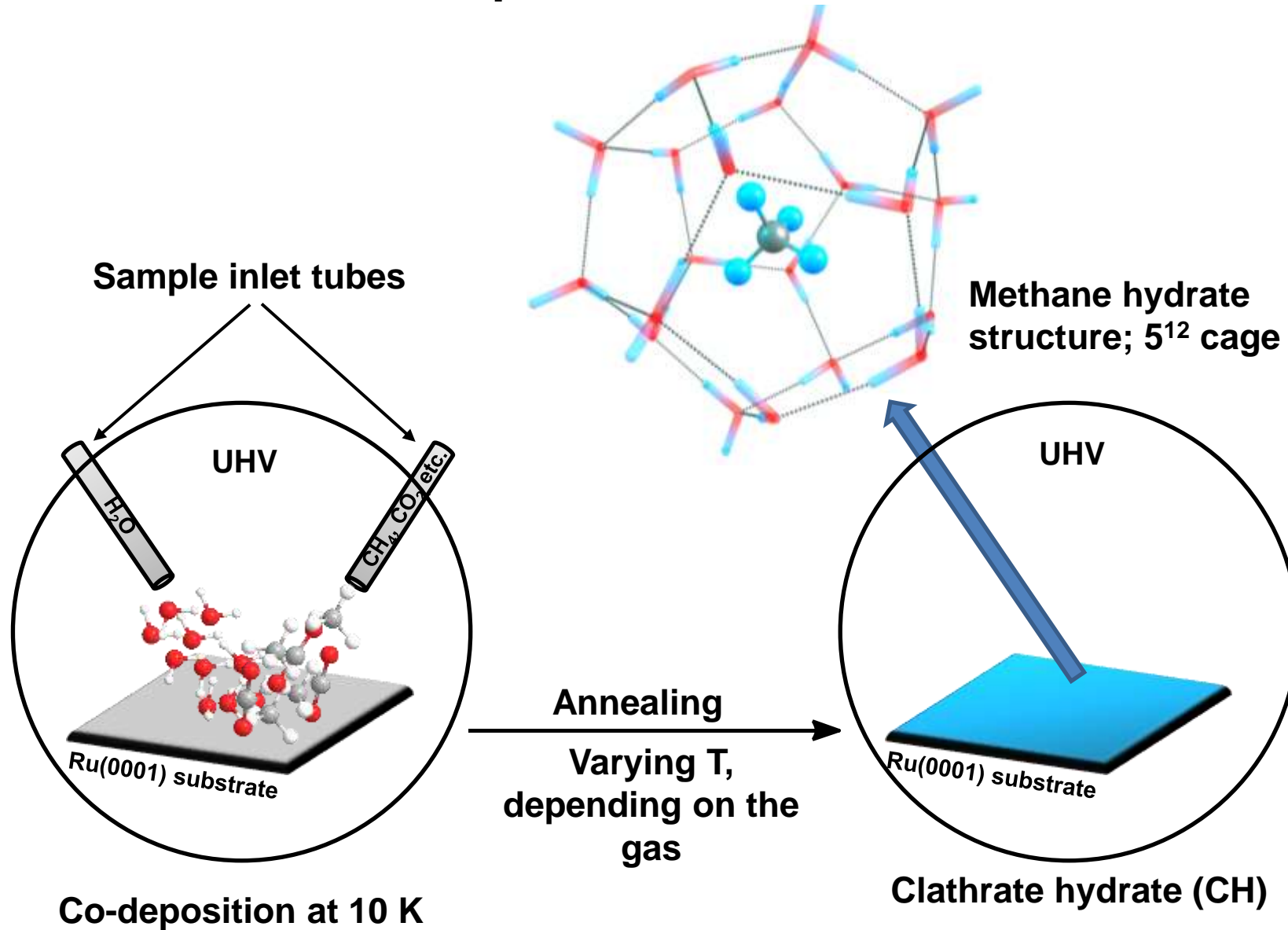
Silicates and carbonaceous material – 0.01-0.5 μm

Arumainayagam, C. R. *et al.*, *Chem. Soc. Rev.*, **2019**, 48, 2293–2314

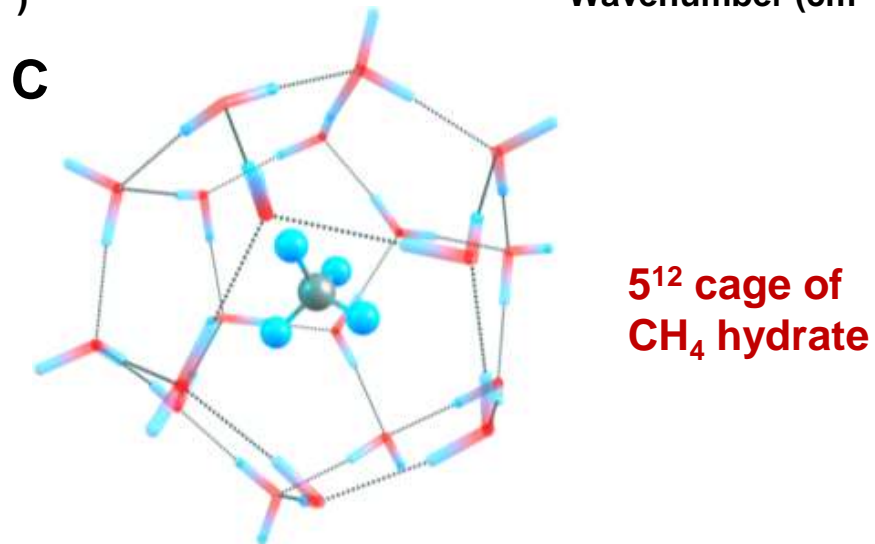
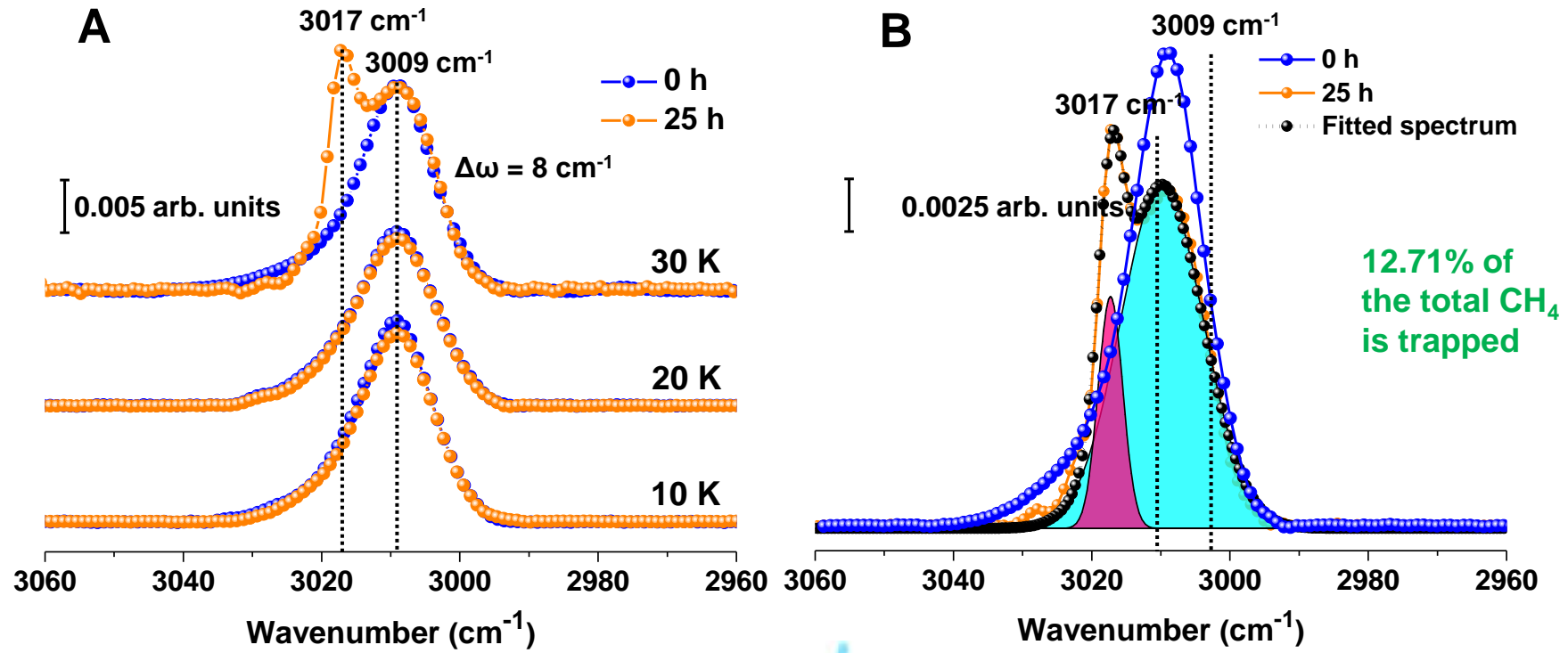
Clathrate hydrates in interstellar environment

Ghosh, J. *et al.*, *Proc. Natl. Acad. Sci. U.S.A.*, **2019**, 116, 1526-1531

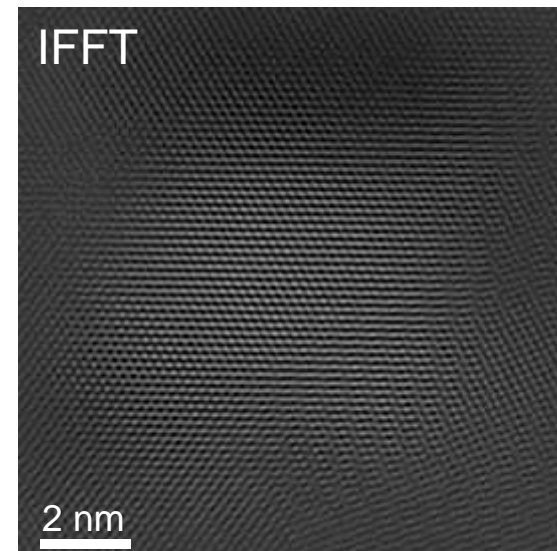
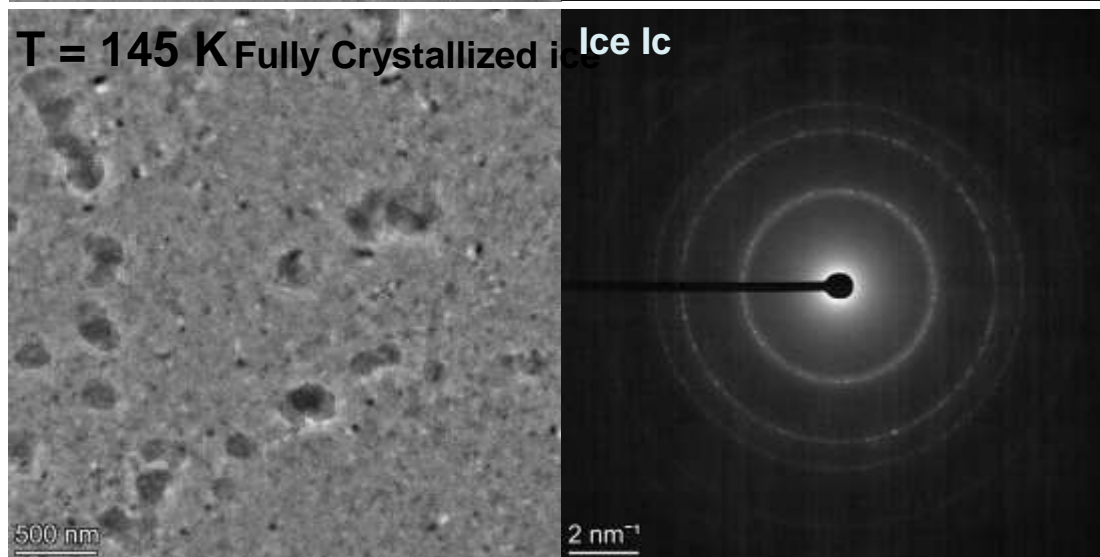
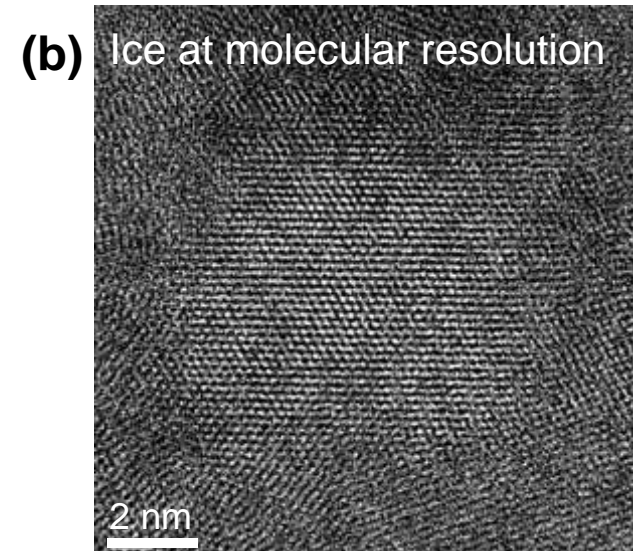
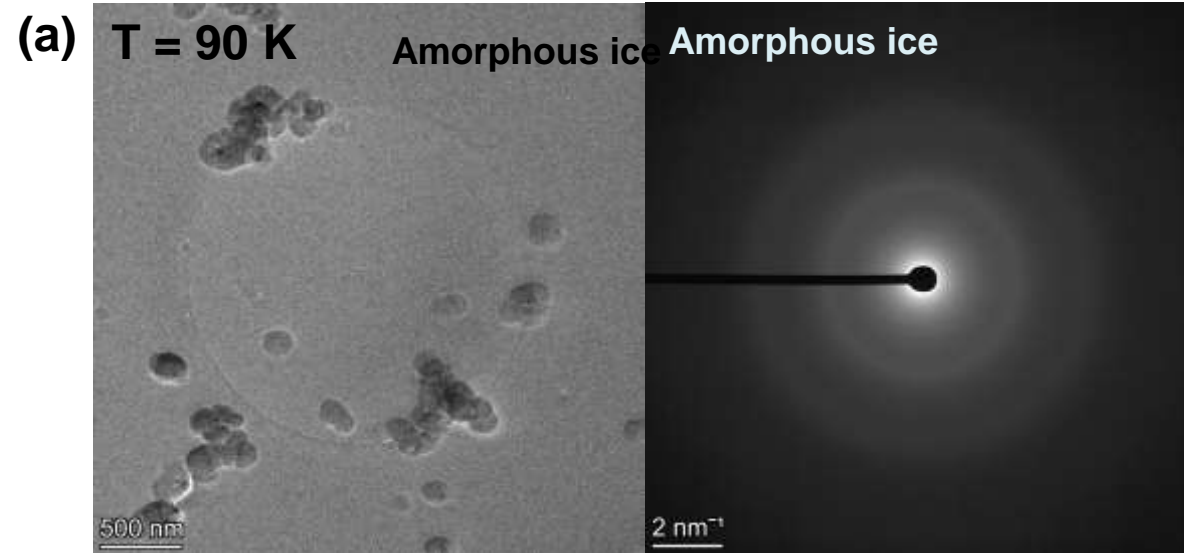
Experimental method



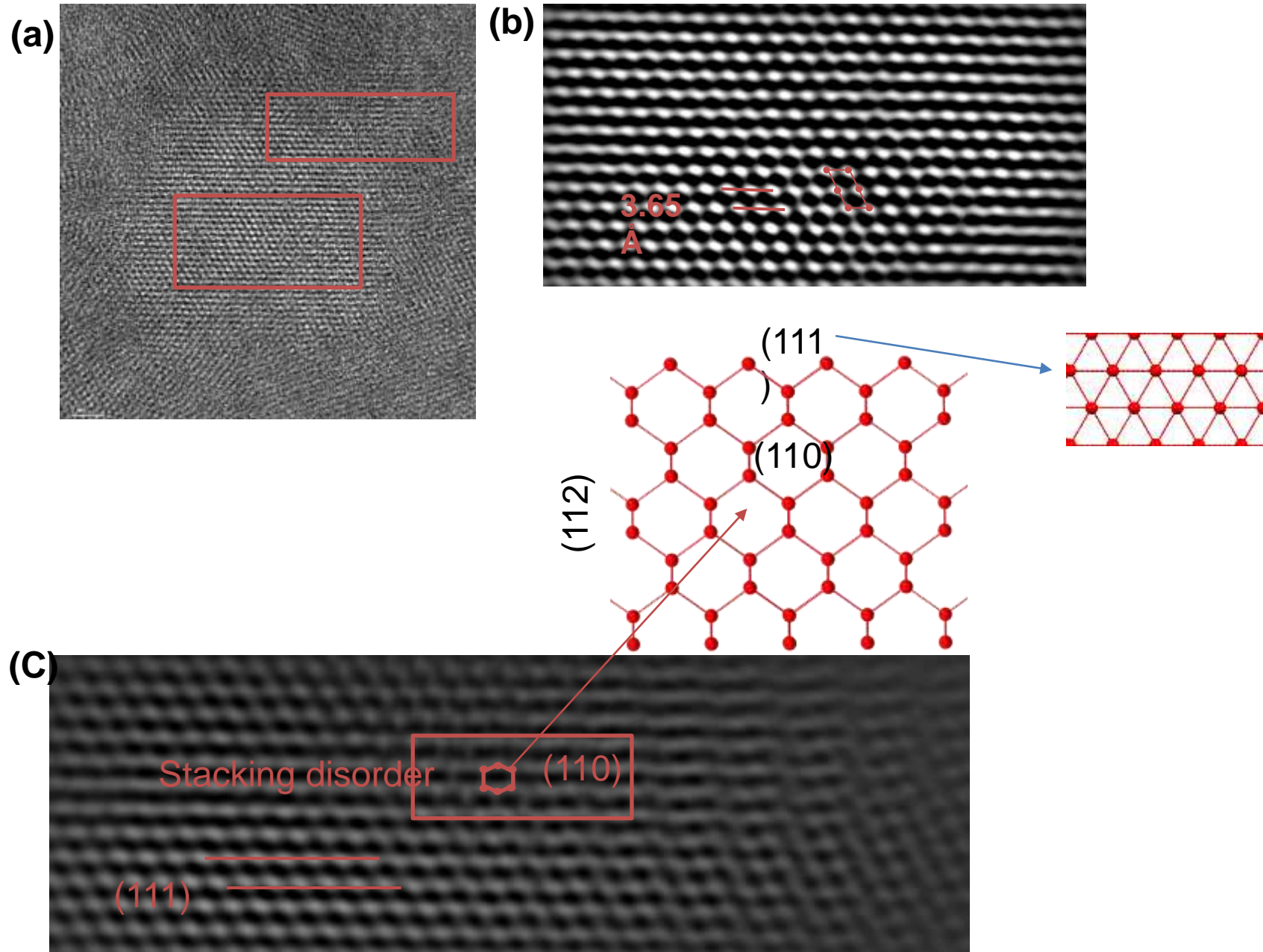
Clathrate hydrates in interstellar environment



Observing growth of crystalline ice from amorphous ice



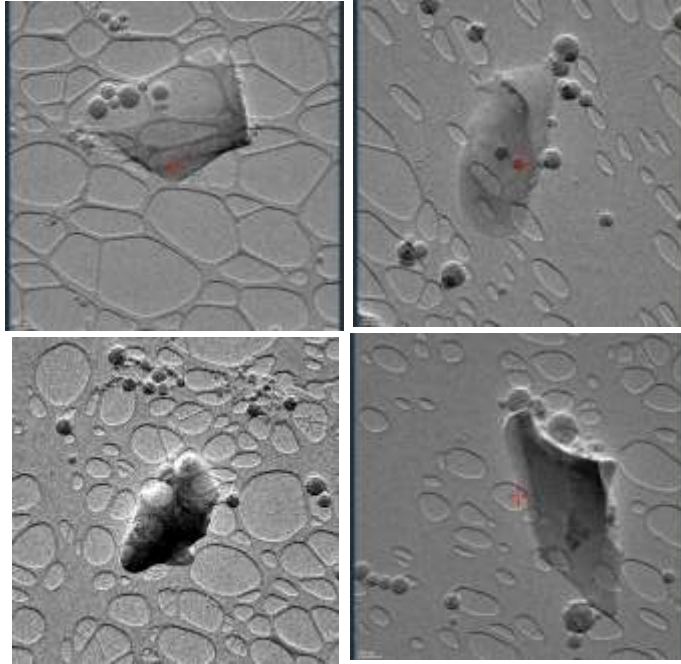
Imaging cubic ice at molecular resolution



Electron diffraction of nanometer-scale crystals of clathrate hydrate

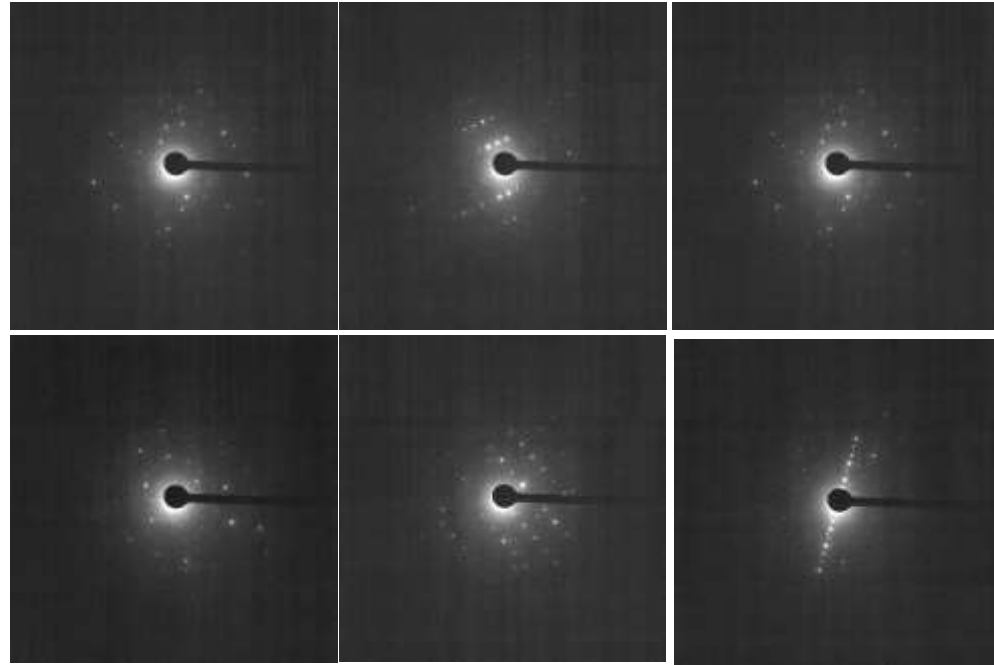
(a)

THF-CH₄ Clathrate hydrate crystal

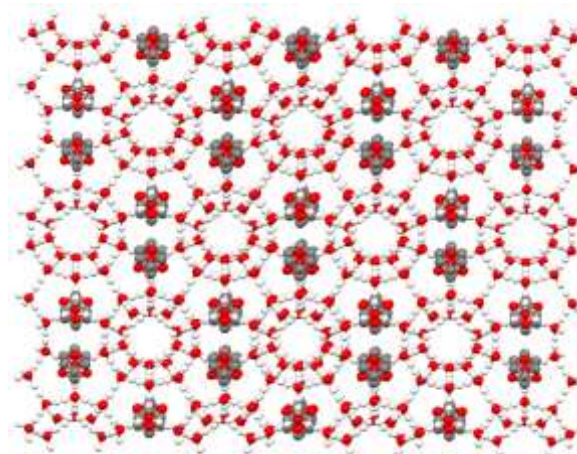
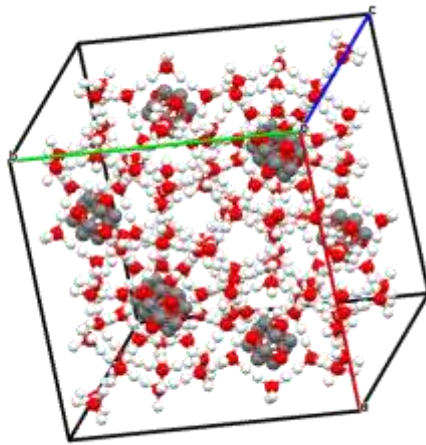


(b)

3 D electron diffraction



(c)



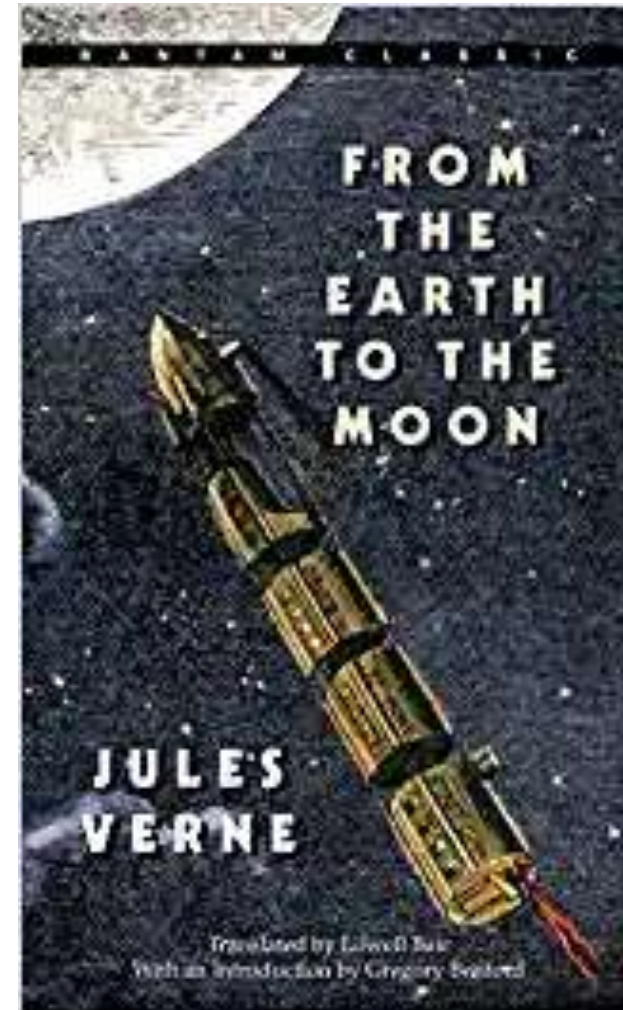
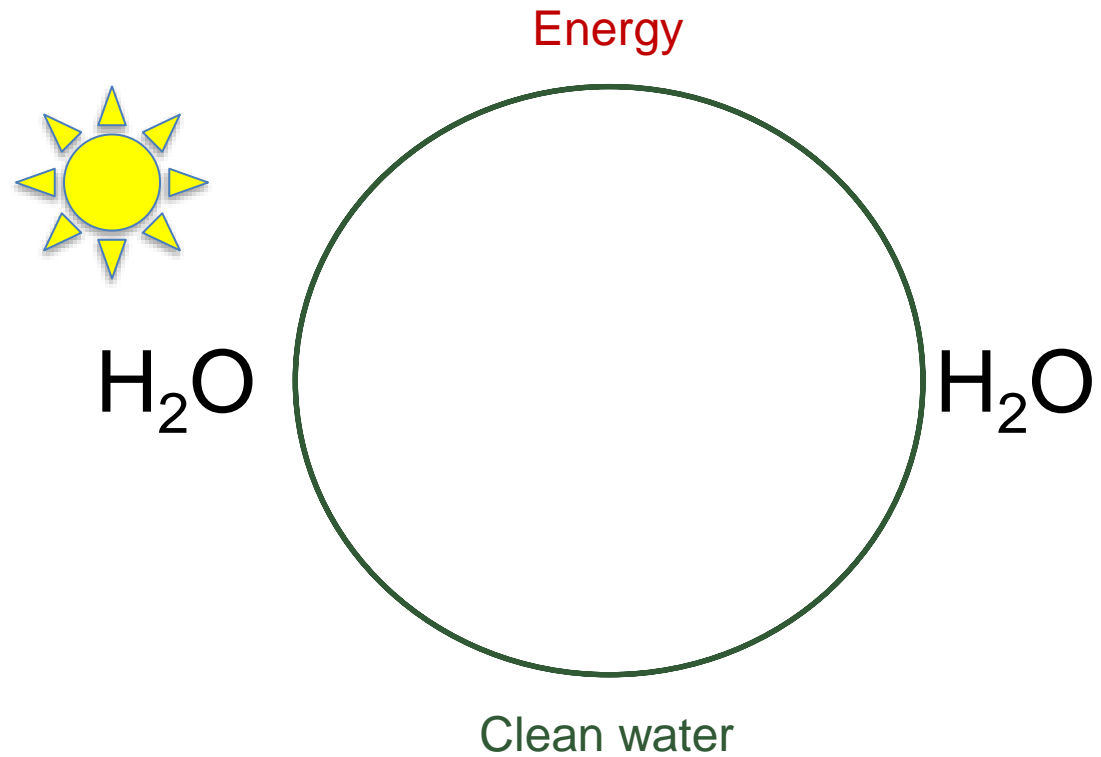
Crystal structure





International Centre for Clean Water

Our dreams become reality with materials





<https://www.youtube.com/watch?v=fiJyptbXBtM>

An ocean of
opportunities

Water presents a unique
opportunity to find a purpose in life.



Earthrise, taken on December 24, 1968, by Apollo astronaut William Anders.
From Wikipedia

Conclusions

Affordable clean water with advanced materials is demonstrated at scale.

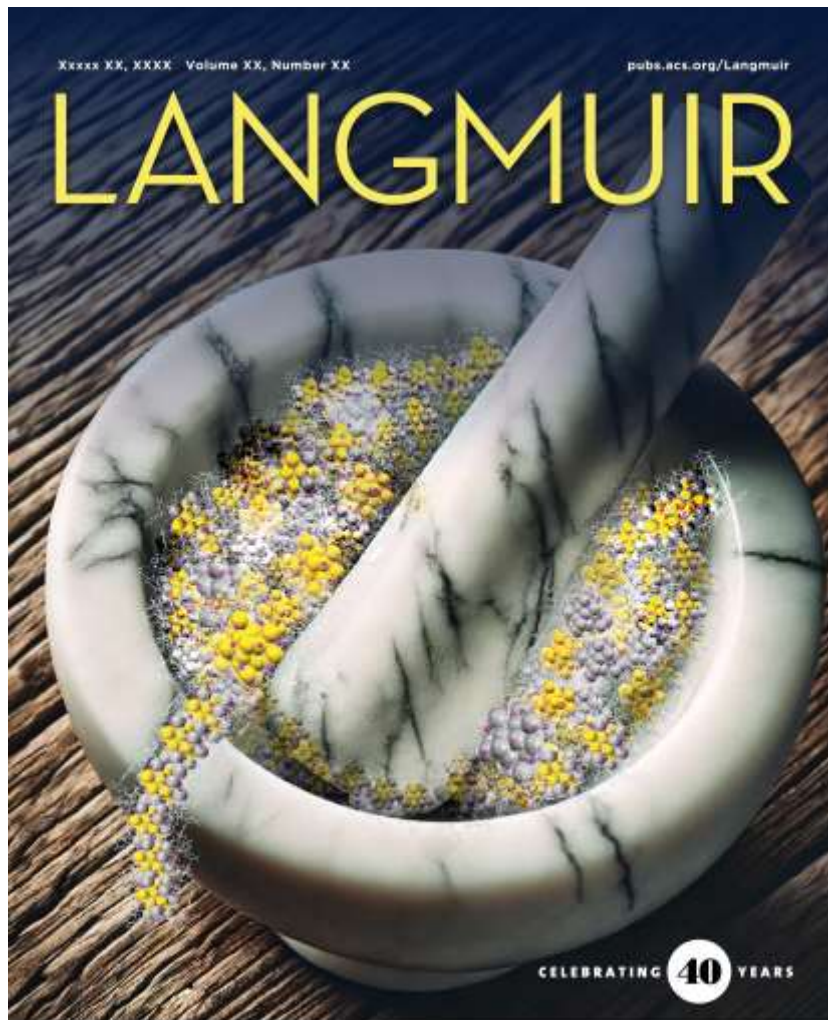
Natural minerals break spontaneously in charged water microdroplets.

Clathrate hydrates exist in ultrahigh vacuum.

Implications of all these are profound.

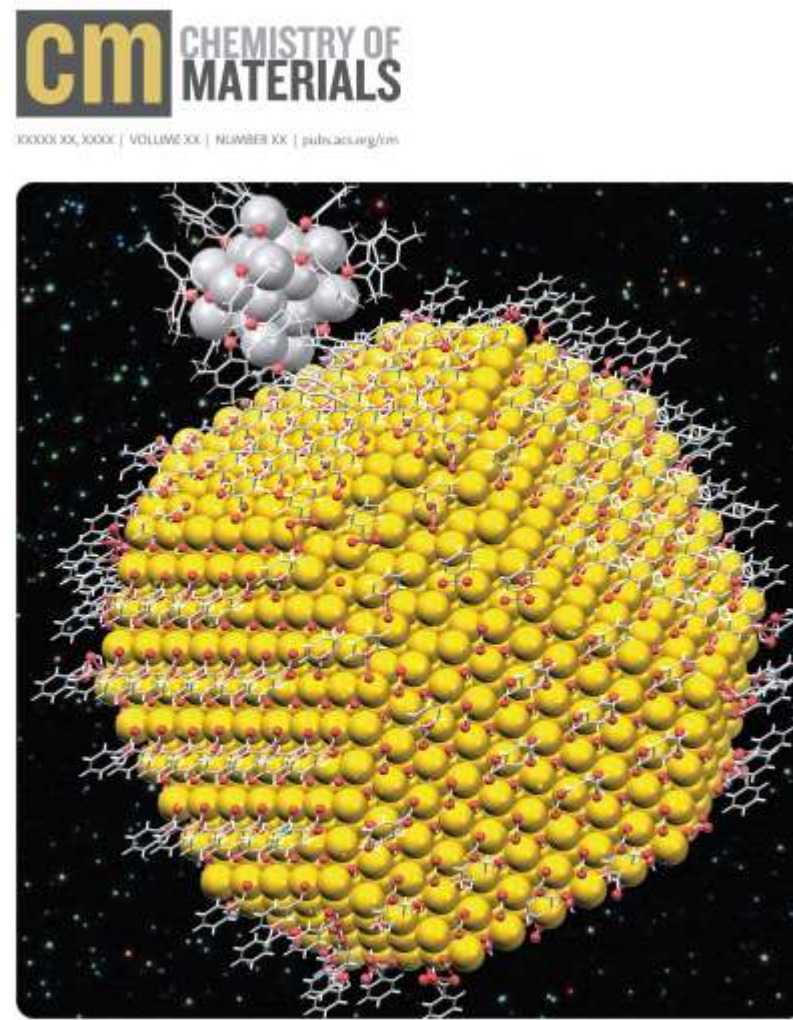
New research is needed in these areas.

Affordable, inclusive, sustainable and contextual excellence



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Many Outstanding Individuals



The AMRIT Team, 2013





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Avula Anil Kumar, Chennu Sudhakar, Sritama Mukherjee, Anshup, and Mohan Udhaya Sankar

Funding: Department of Science and Technology, Government of India

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MS Theses: Ananthu Mahendranath, Ramesh Kumar Soni

>25 Post-doctoral fellows, >130 masters students and visitors





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Manswita Mandal for help with the slides