Since 1959

Viksit Bharat

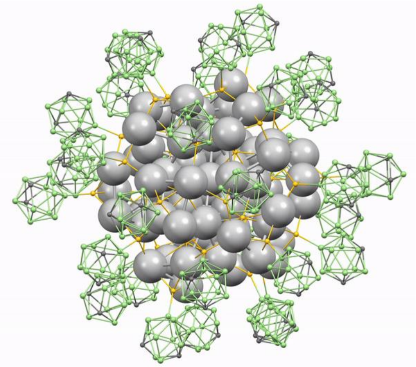
Water, Droplets and Ice

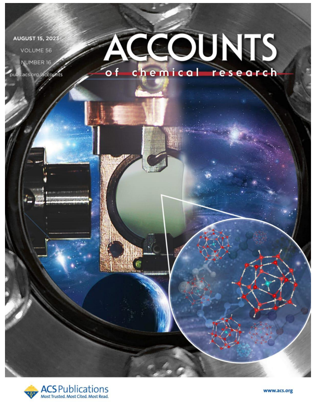
Examples of Science in Action

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.





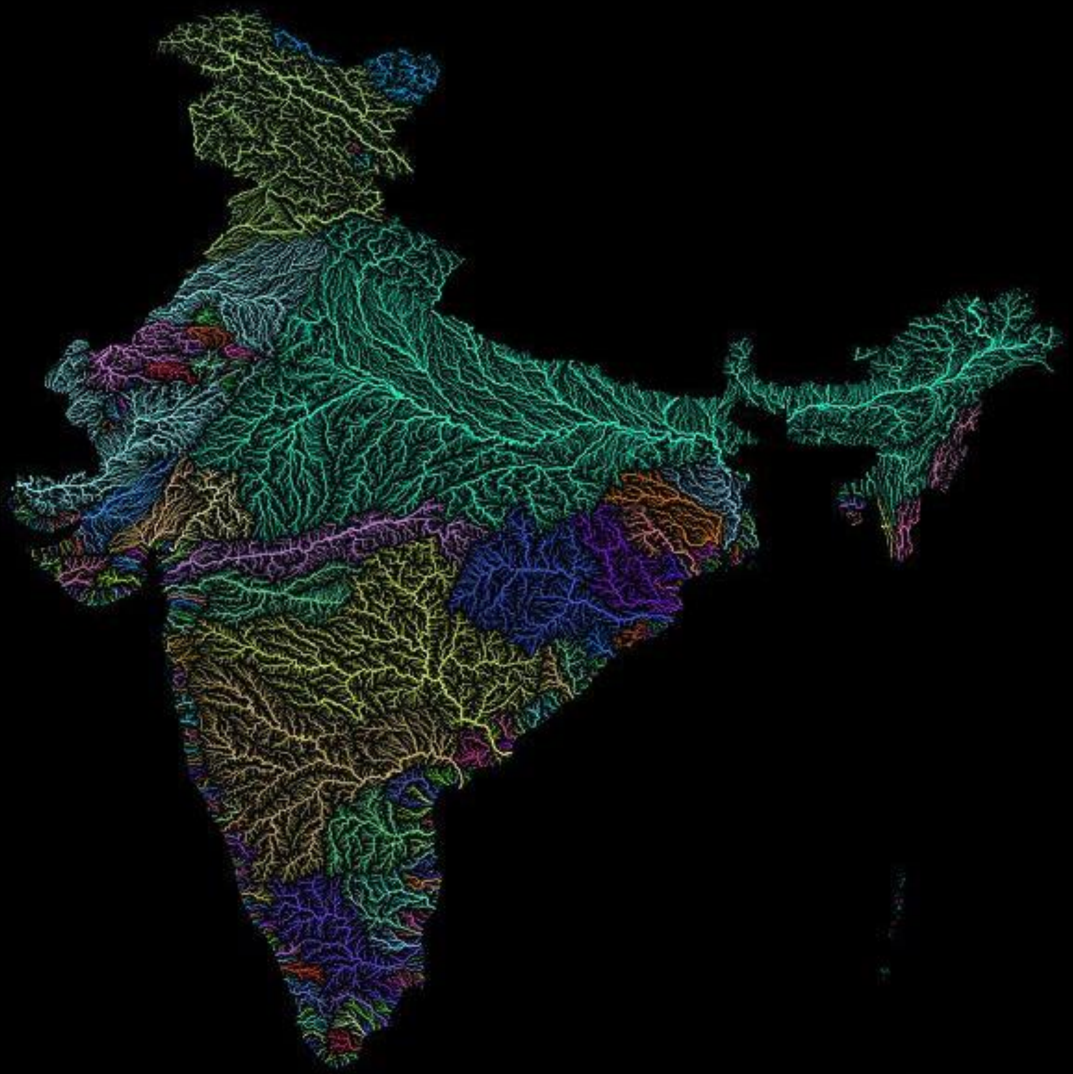
Professor-in-charge

International Centre for Clean Water

Associate Editor
ACS Sustainable Resource Management

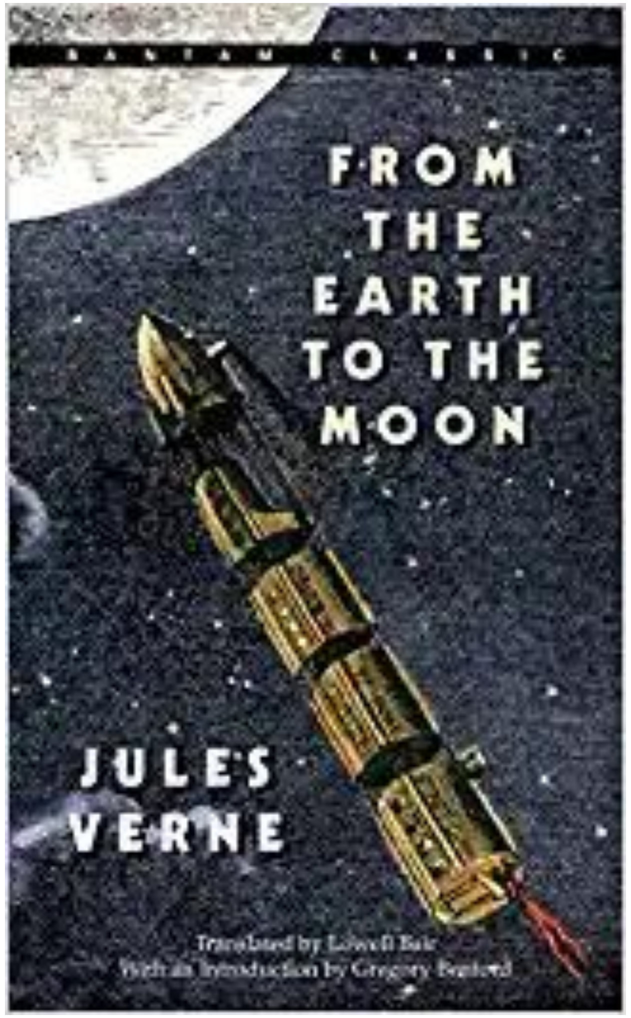
National Science Day Lectures, IIT Ropar, February 28, 2025


“Pale blue dot” Voyager 1 Feb. 14, 1990
Water is the most important inheritance of our planet



From S. Vishwanath

Our dreams become reality with materials



Affordable clean water is a problem of advanced materials

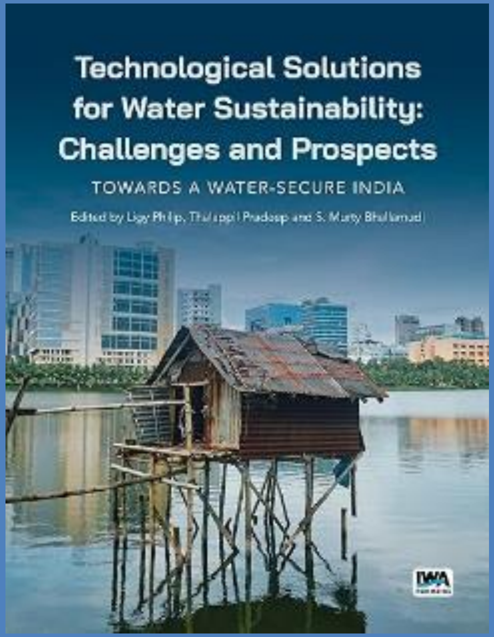
New adsorbents

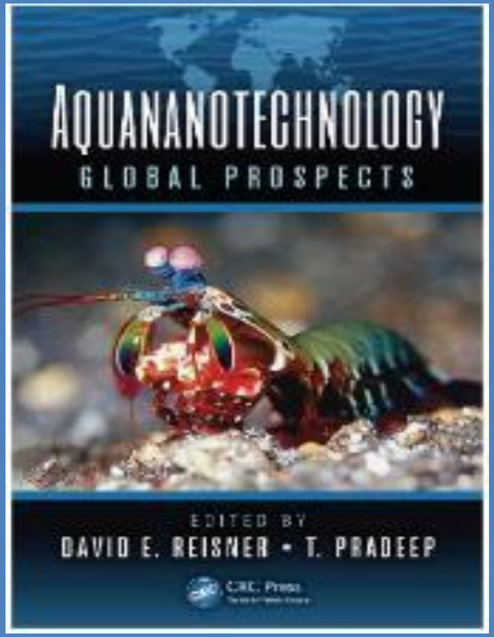
New sensors

New catalysts

Novel phenomena

New devices





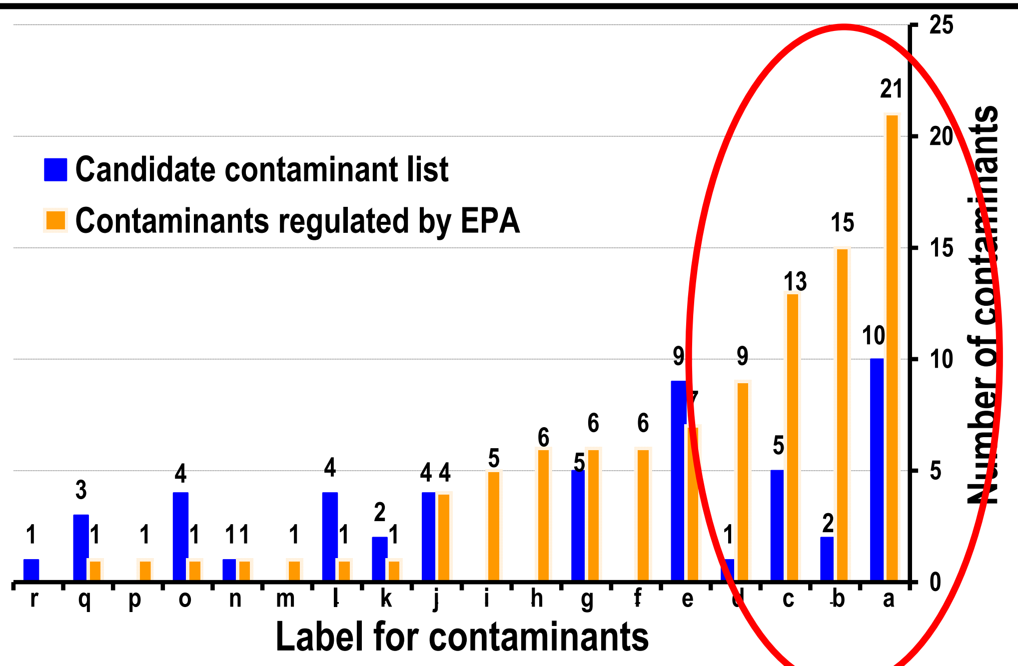
Water purification, history

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	*Silent Spring* 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)

T. Pradeep and Anshup, *Thin Solid Films*, 2009

Future of water purification: An enigma with some pointers



(a): Halogenated organic (b): Metal (c): Organochlorine pesticide (d): Inorganic salt (e): Biological contaminant (f): Nuclear (g): Benzo derivative (h): Carbamate pesticide (i): Pesticides (others) (j): Unclassified (k): Triazine derivative pesticide (l): Organophosphorus pesticide (m): Organobromine pesticide (n): Non-metal (o): Nitrophenol derivative, (p): Dioxin, (q): Benzo and halogenated organic (r): Organometallics

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

Killugudi 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. Jayachandra Reddy, 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,' Thalappil Pradeep who led the team at IIT Chennai told Chemistry World. He and his student Sreekumaran Nair discovered in 2003 that halocarbons such as carbon tetrachloride (CCl4) completely break down into metal halides and amorphous carbon upon reaction with gold and silver nanoparticles[1].

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 found[2,3] that gold and silver nanoparticles loaded on alumina were indeed able to completely remove endosulfan, malathion and chlorpyrifos - three pesticides that ... water supplies.

Use and recycle

Chemistry world
First ever nanotechnology product for clean water

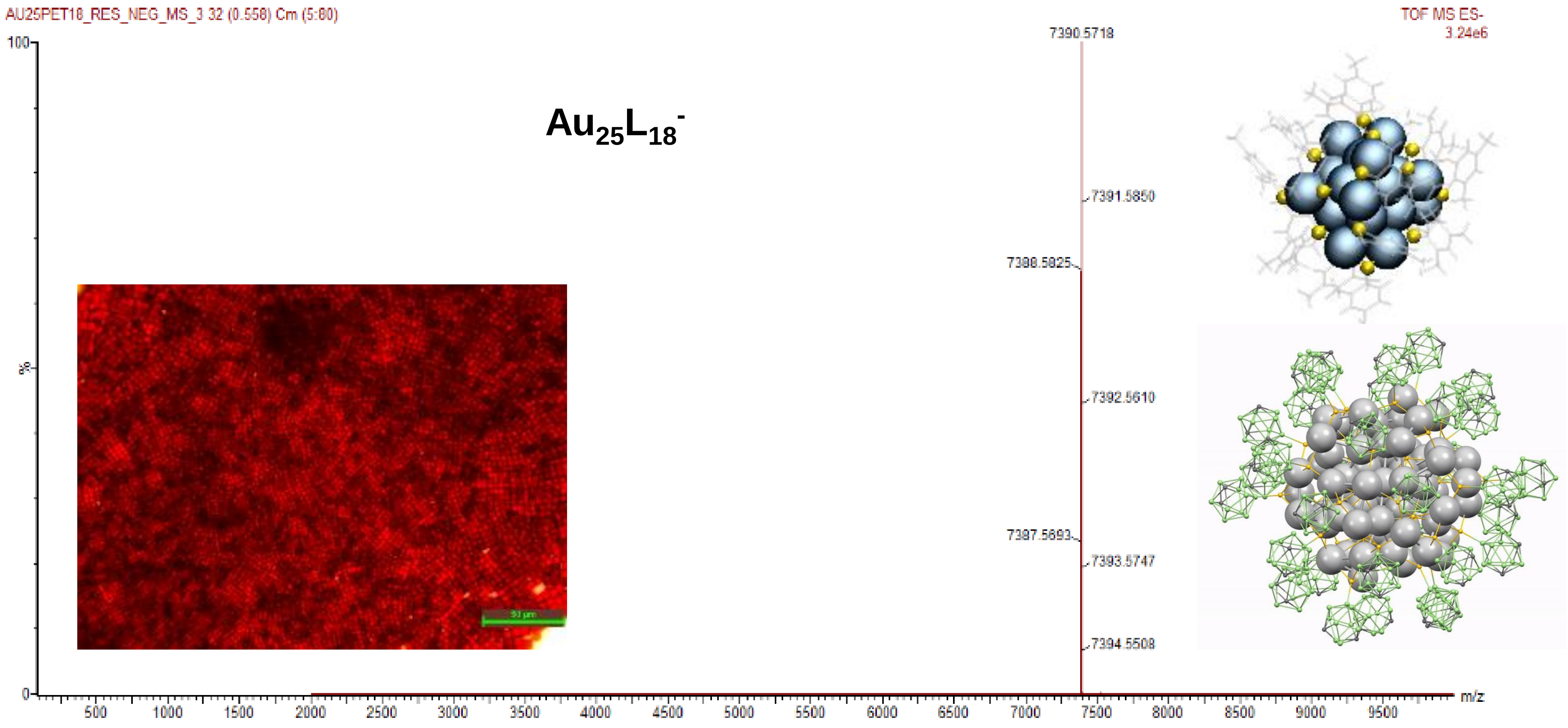
A plant to make supported nanomaterials for water purification; with capacity of 4.5 tons per month, 2007

1. Patents: A method of preparing purified water from water containing pesticides, **Indian patent 200767**
2. Extraction of malatheon and chlorpiryhphos 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

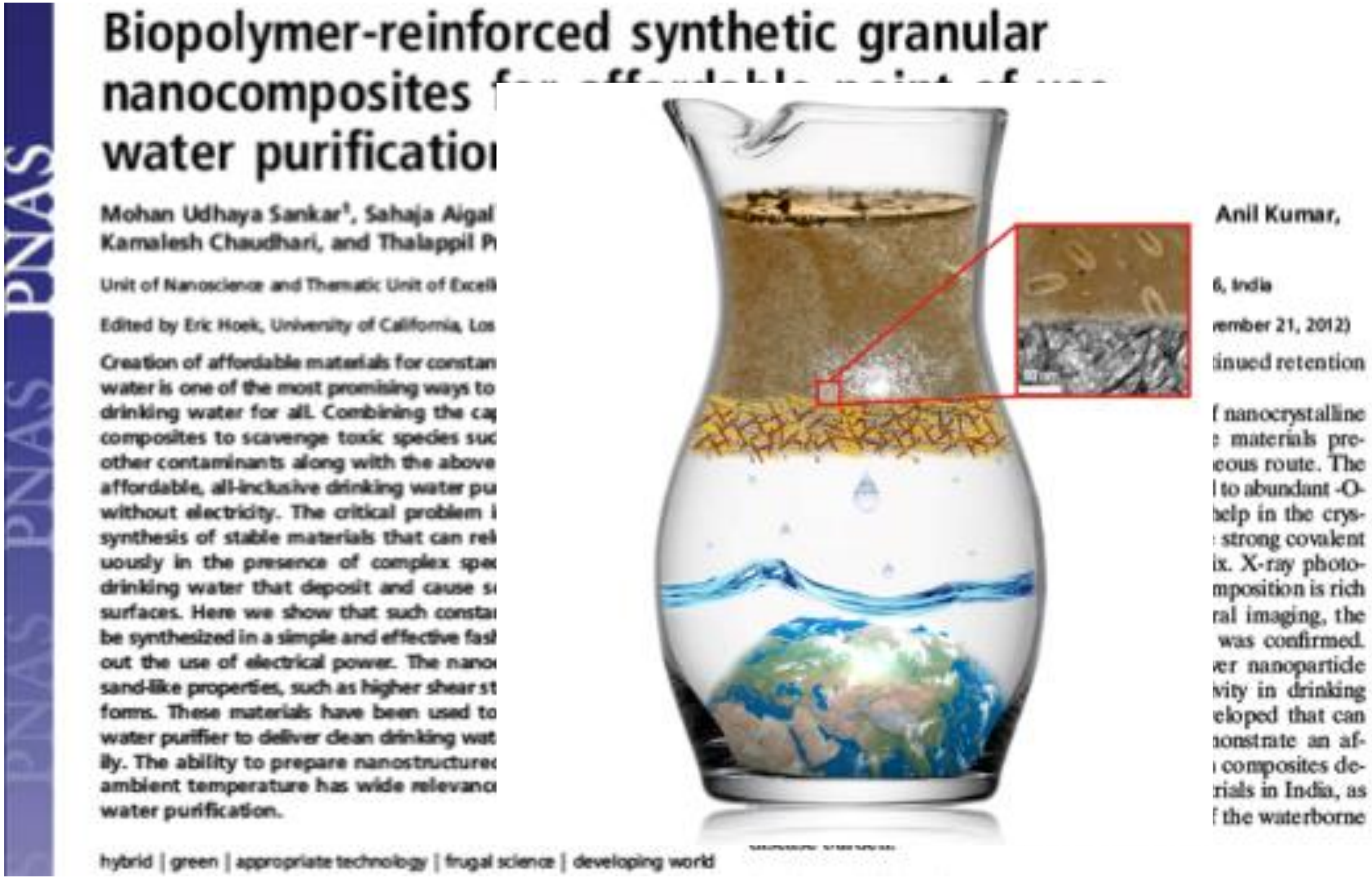


T. Pradeep et. al. *Acc. Chem. Res.* 2018; 2019.

Clean water for everyone

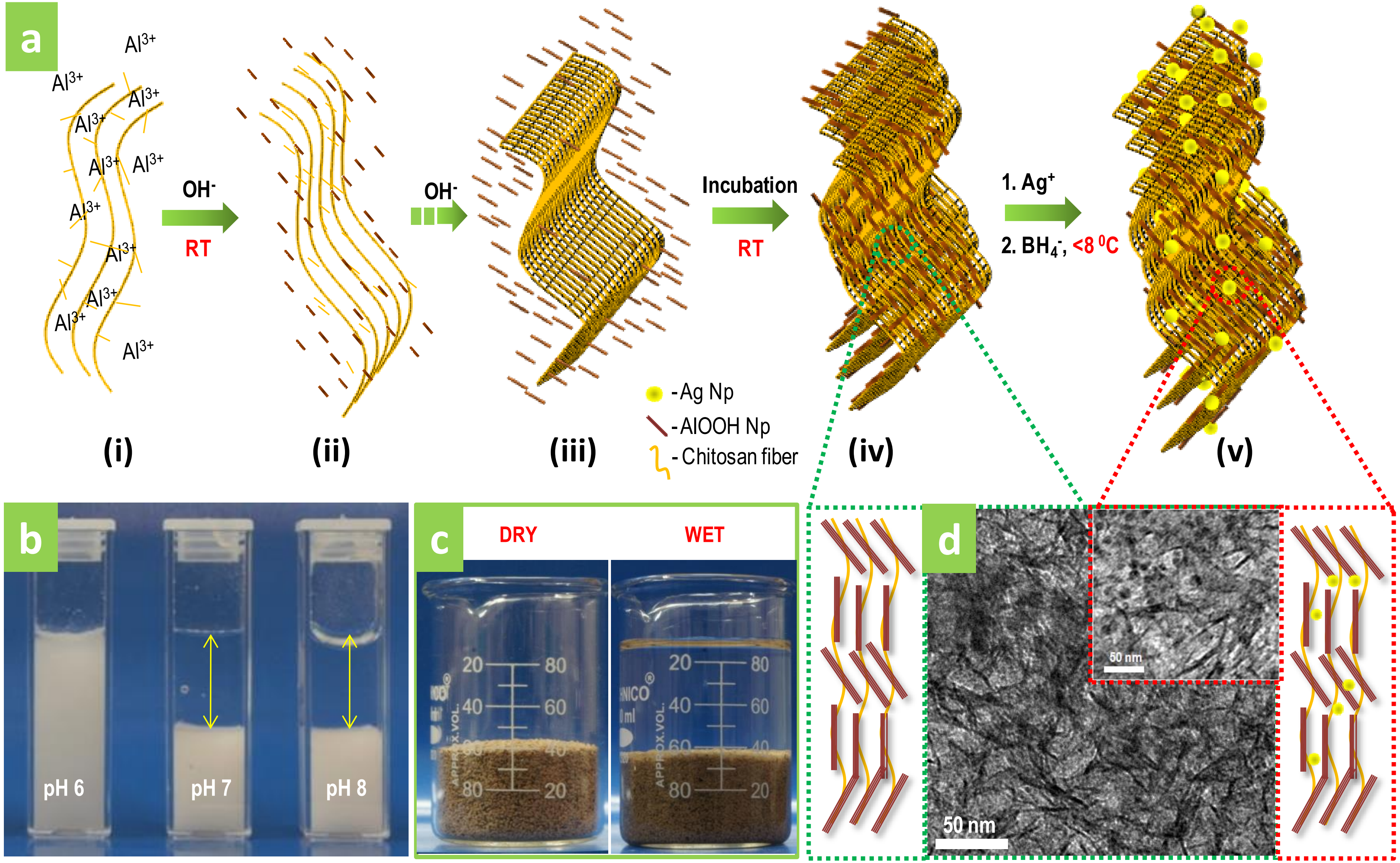
ACS Sustainable Chemistry & Engineering Editorial, December 2016

Water positive materials

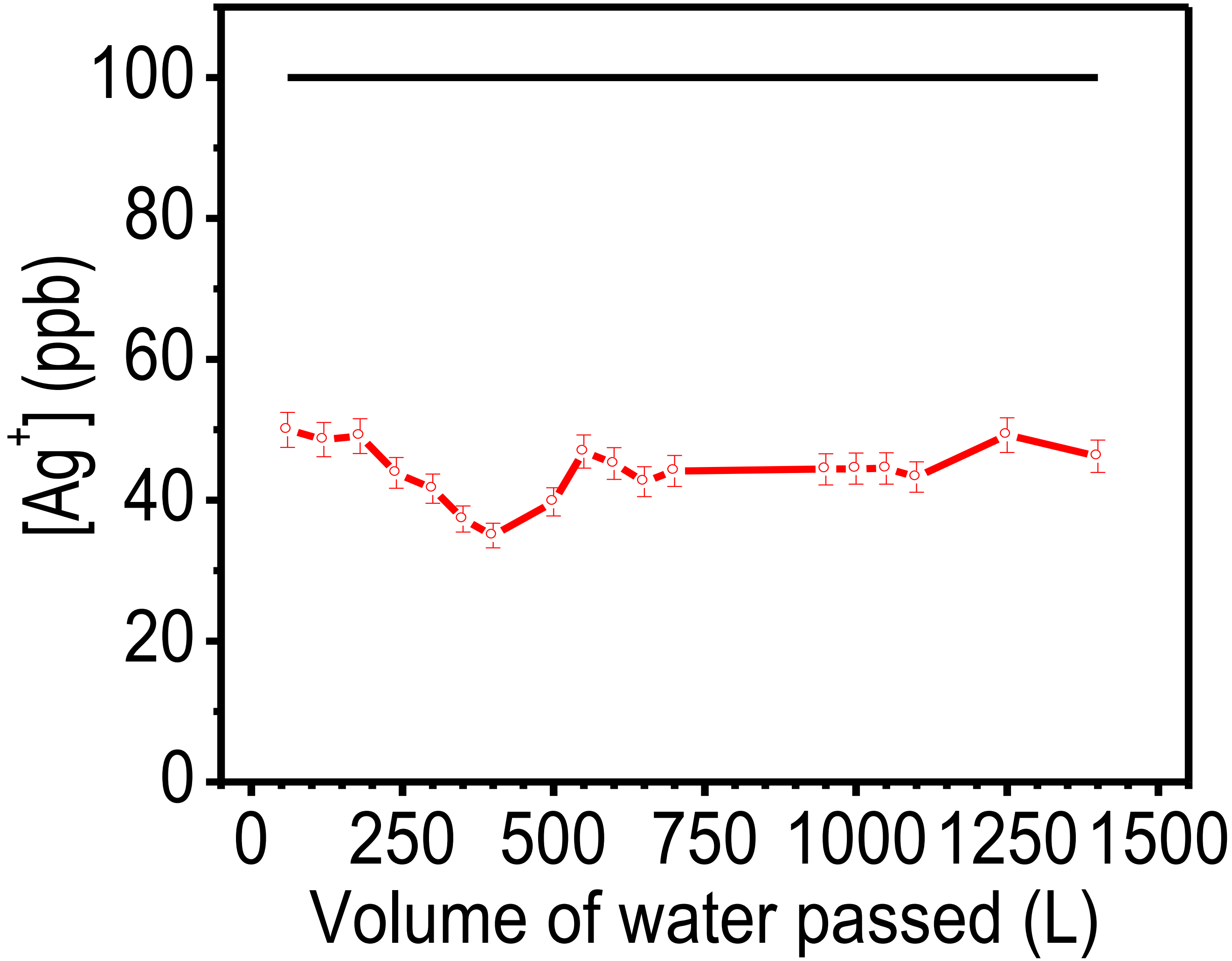


M. Udhaya Sankar, et. al. *Proc. Natl. Acad. Sci.,* 110 (2013) 8459-8464.

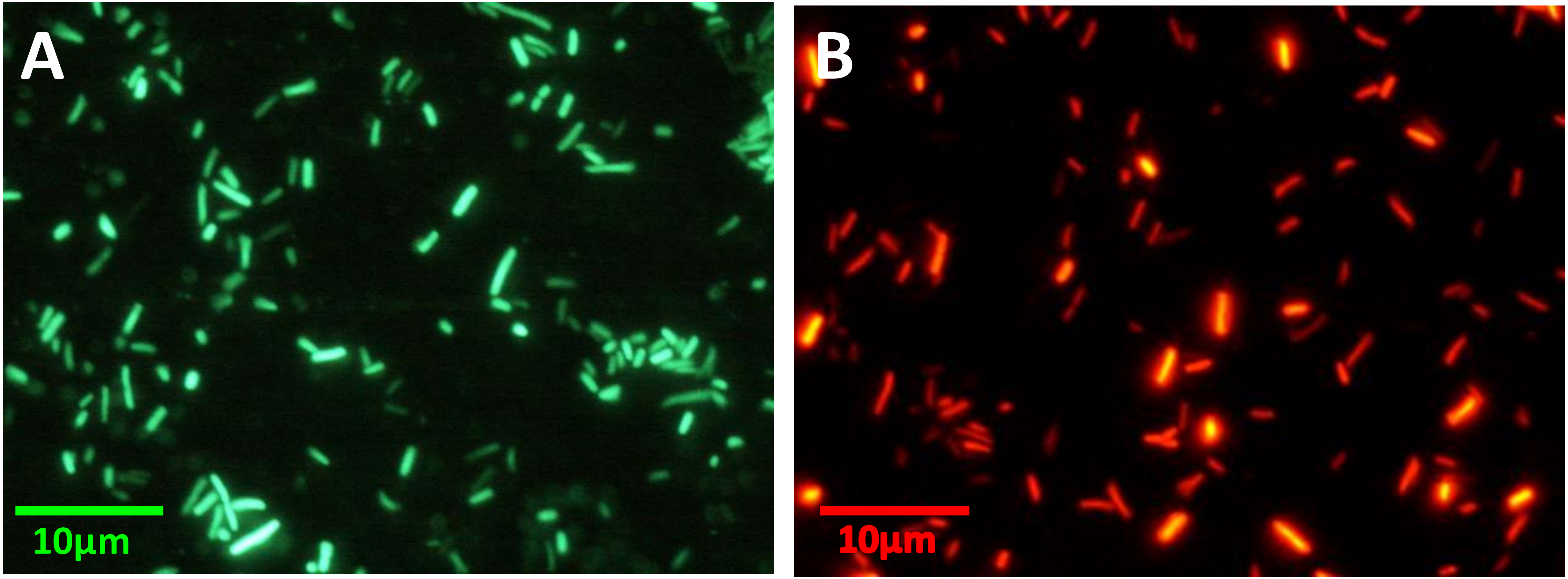
How to make?


a
Al3+
OH-
RT
OH-
Incubation
RT
1. Ag+
2. BH4-, <8 0C
- Ag Np
- AlOOH Np
- Chitosan fiber
(i)
(ii)
(iii)
(iv)
(v)
b
pH 6
pH 7
pH 8
c
DRY
WET
d
50 nm
50 nm

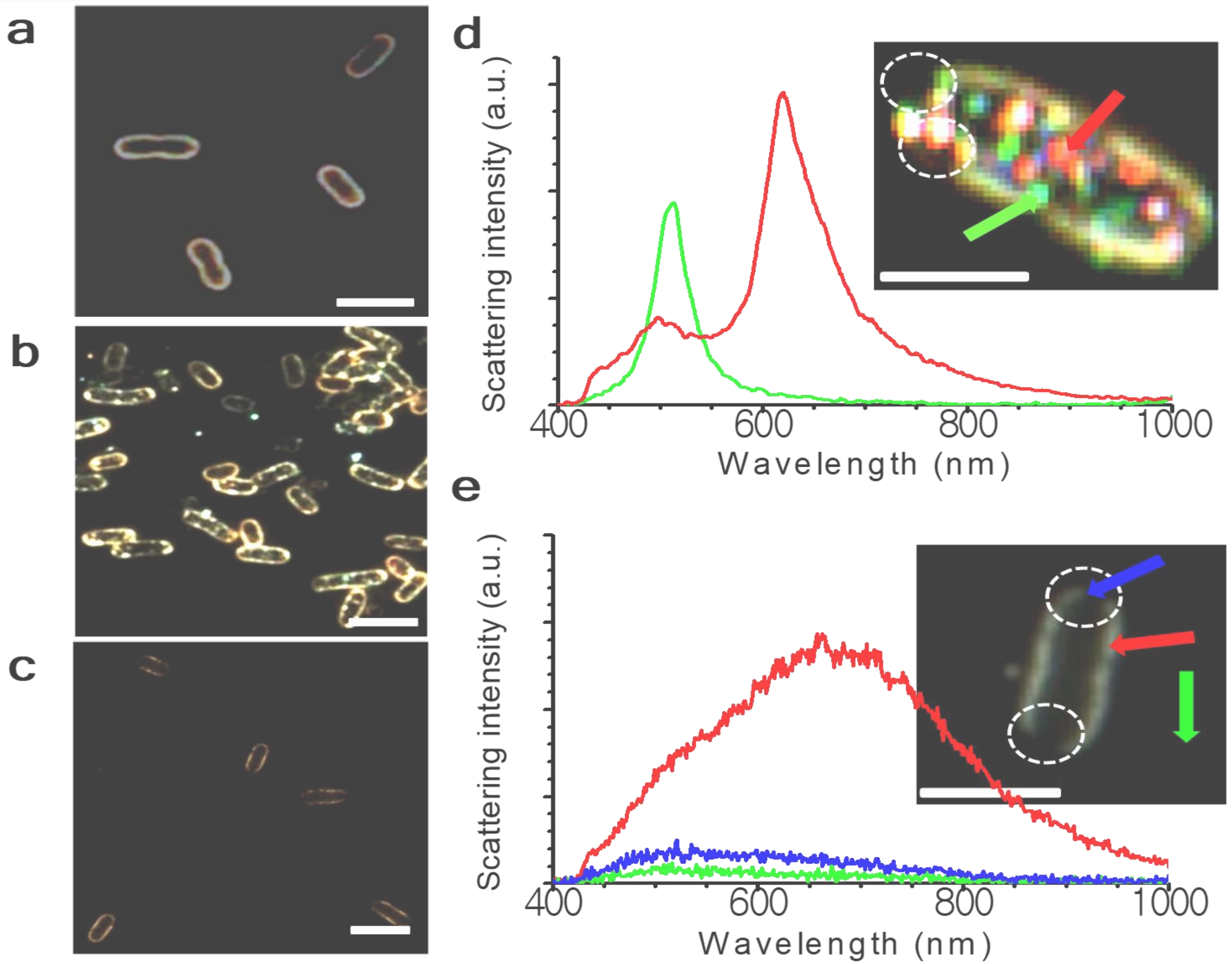
What is special?



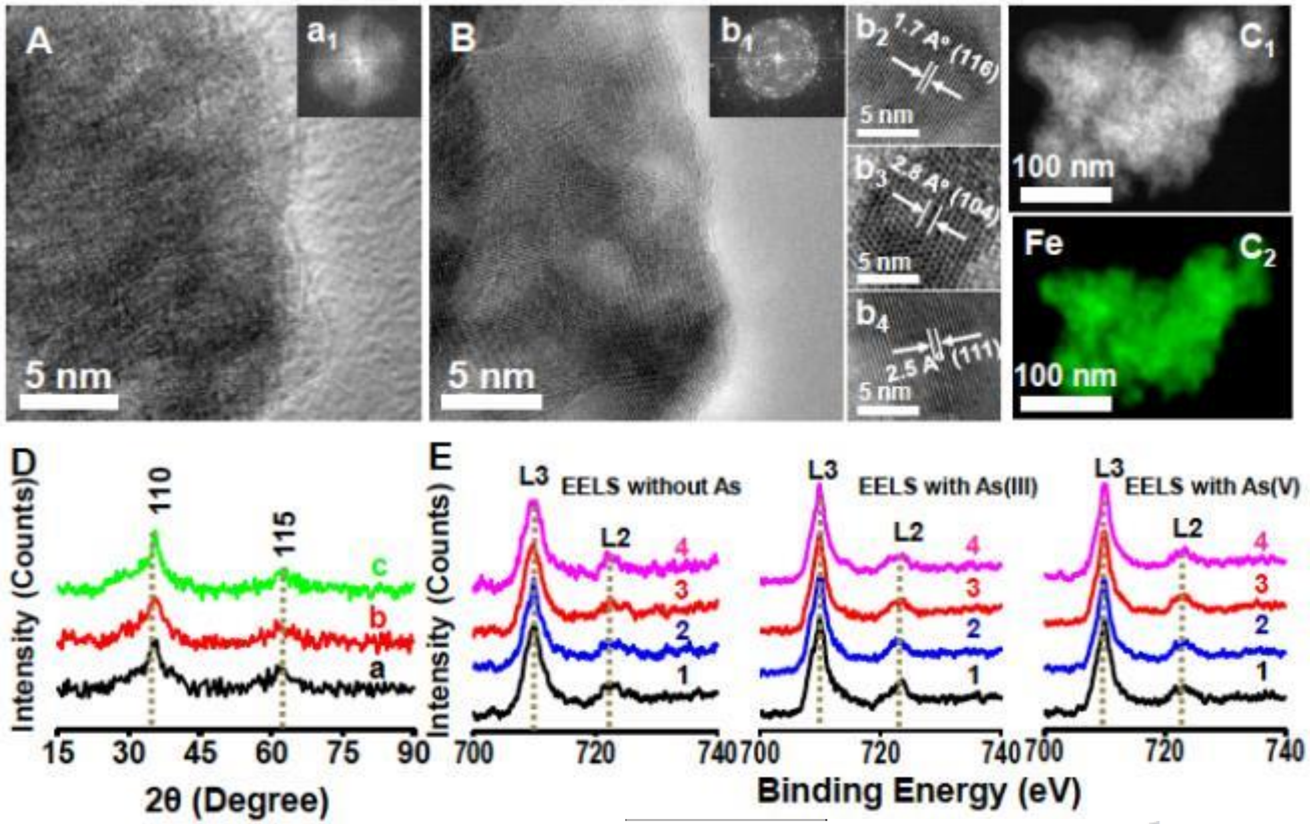
Live/dead staining experiments



No nanotoxicity



Variety of materials




Author Proof

www.advmat.de

ADVANCED MATERIALS

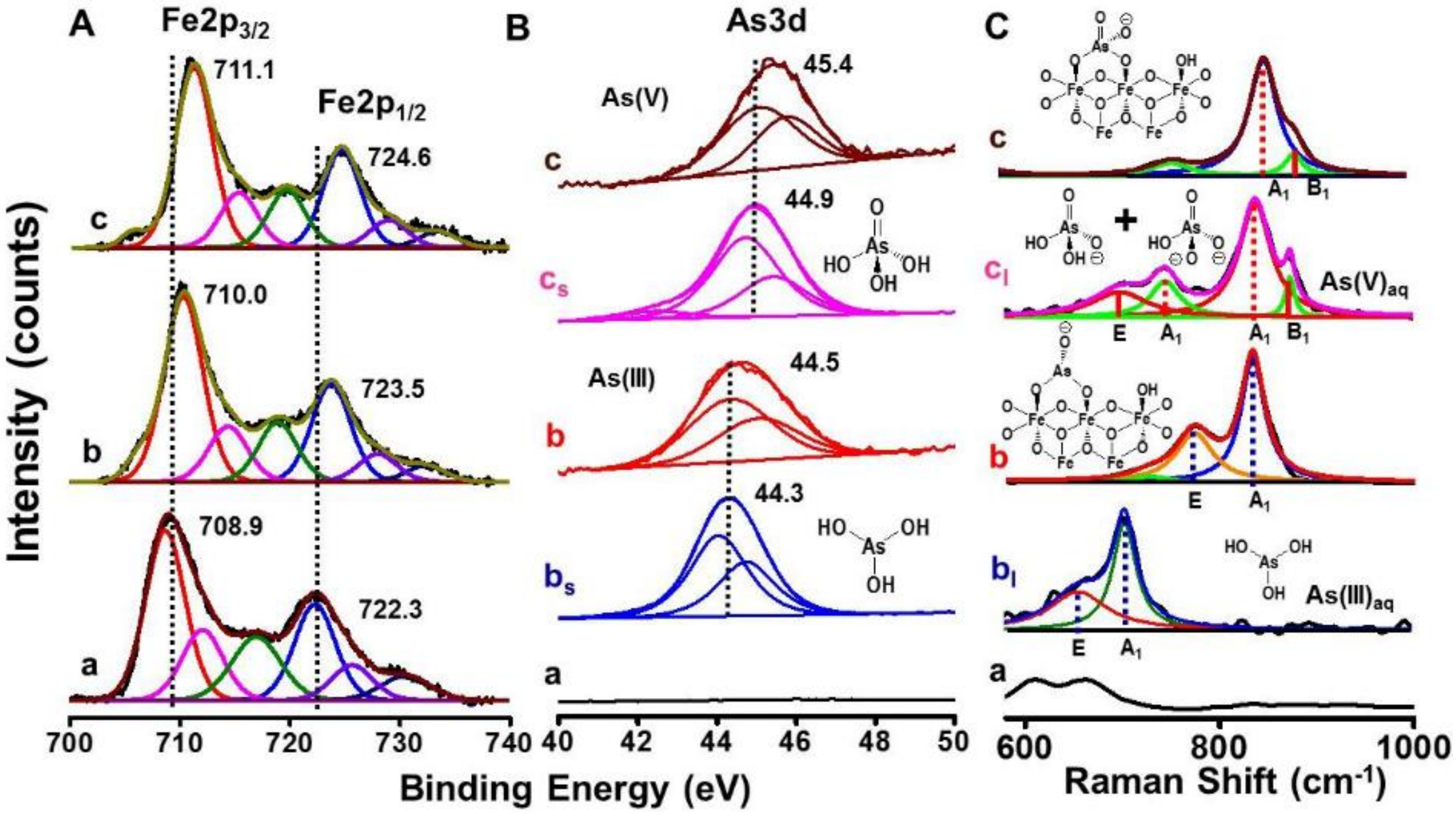
Communication

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

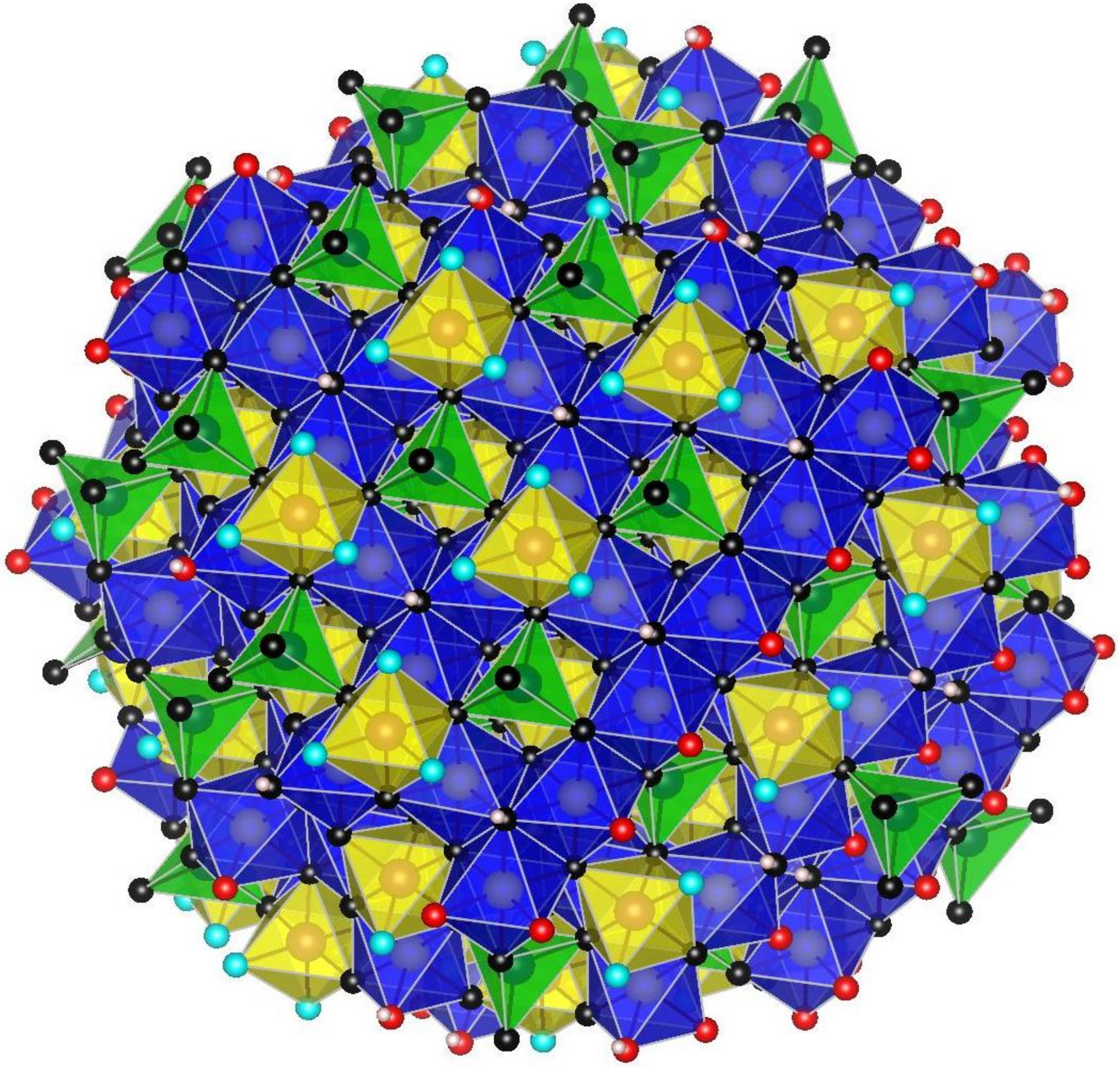
By Avula Anil Kumar, Anirban Som, Paolo Longo, Chennu Sudhakar, Radha Gobinda Bhuin, Soujit Sen Gupta, Anshup, Mohan Udhaya Sankar, Amrita Chaudhary, Ramesh Kumar, and T. Pradeep*

A. Anil Kumar, et. al. *Adv. Mater.*, 29 (2016) 1604260.

Mechanism – molecular tools

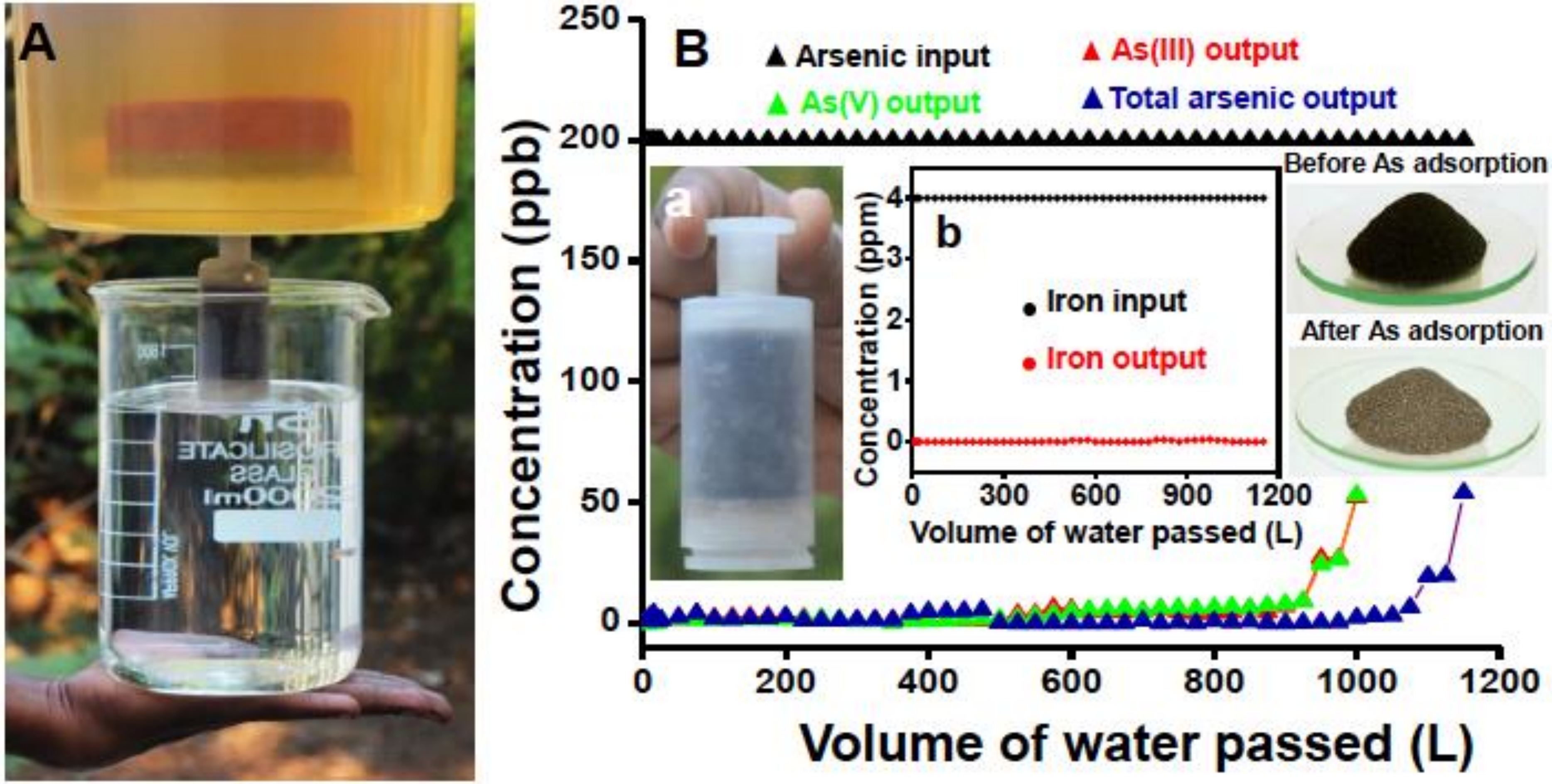


Modeling surfaces



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

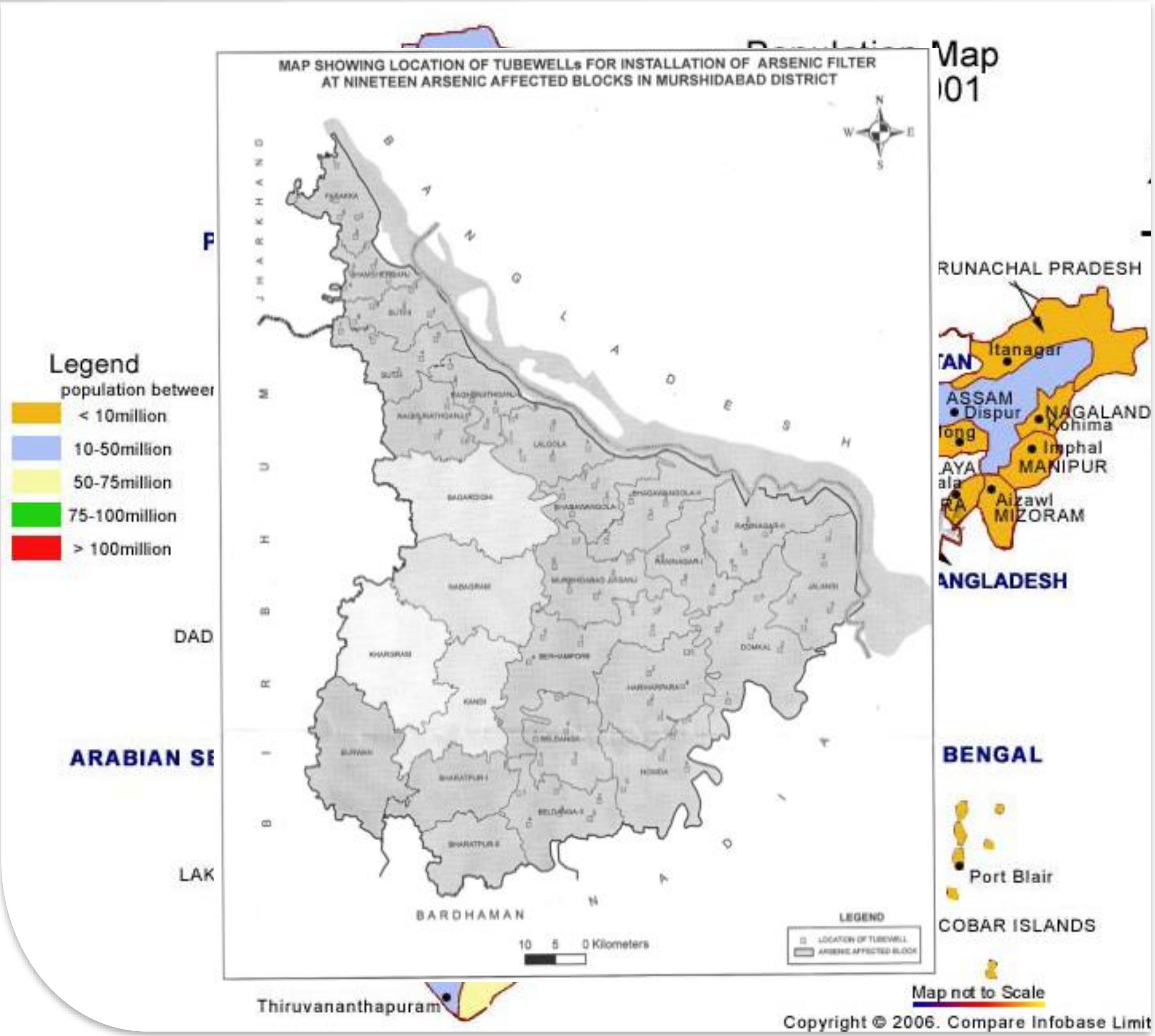
Lab studies



A. Anil Kumar, et. al. *Adv. Mater.*, 29 (2016) 1604260.

Initial pilot studies

Larger pilot studies



Changing the dynamics in the field

- Existing unit for iron and arsenic removal – 20 m^3/h
- Uses activated alumina and iron oxide (old generation of adsorbents)

- Existing unit for iron and arsenic removal – 18 m^3/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
03471-250221
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

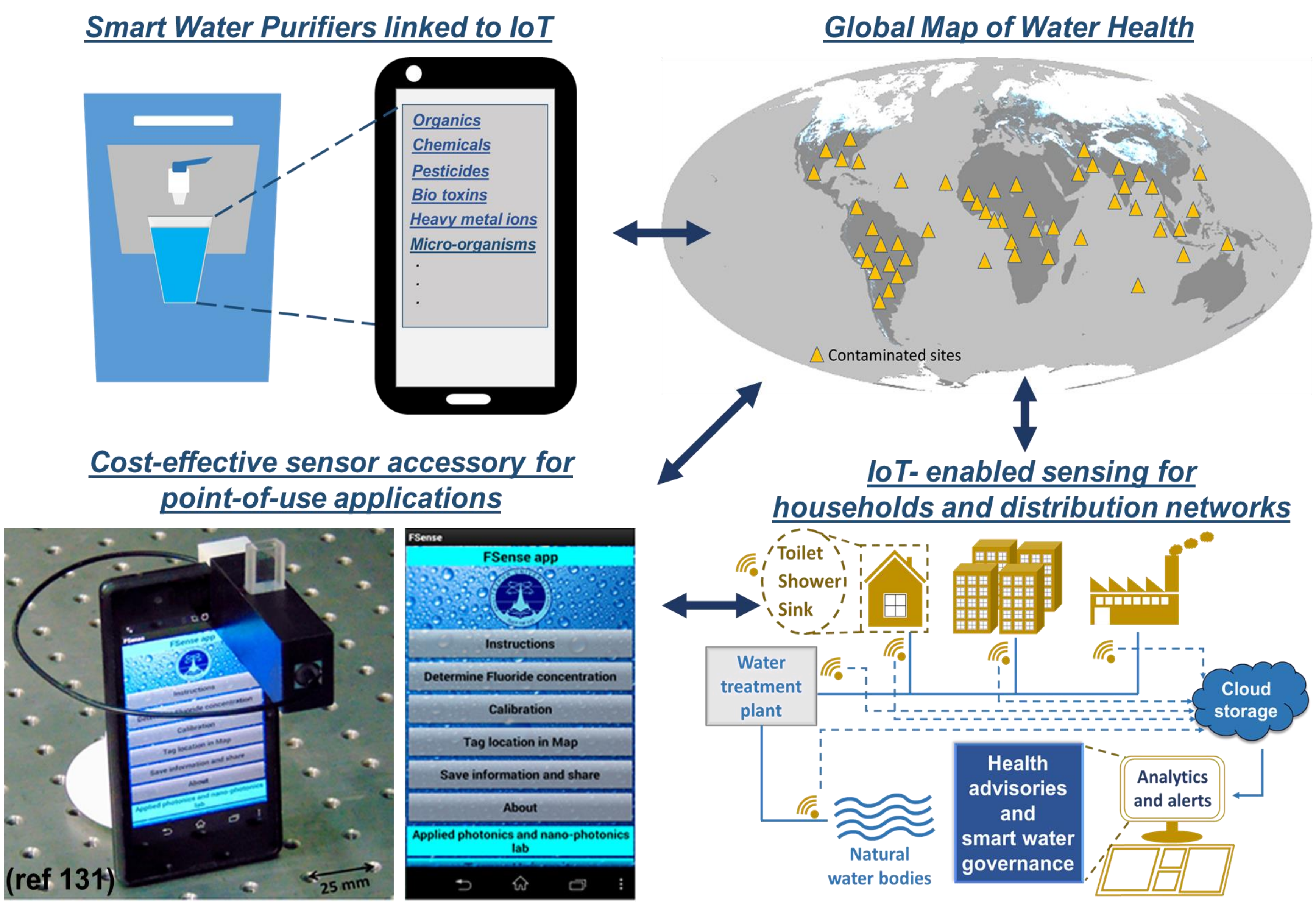
Retrofitted Water Purification Plant
Capacity: 0.1-1 MLD

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 litr 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



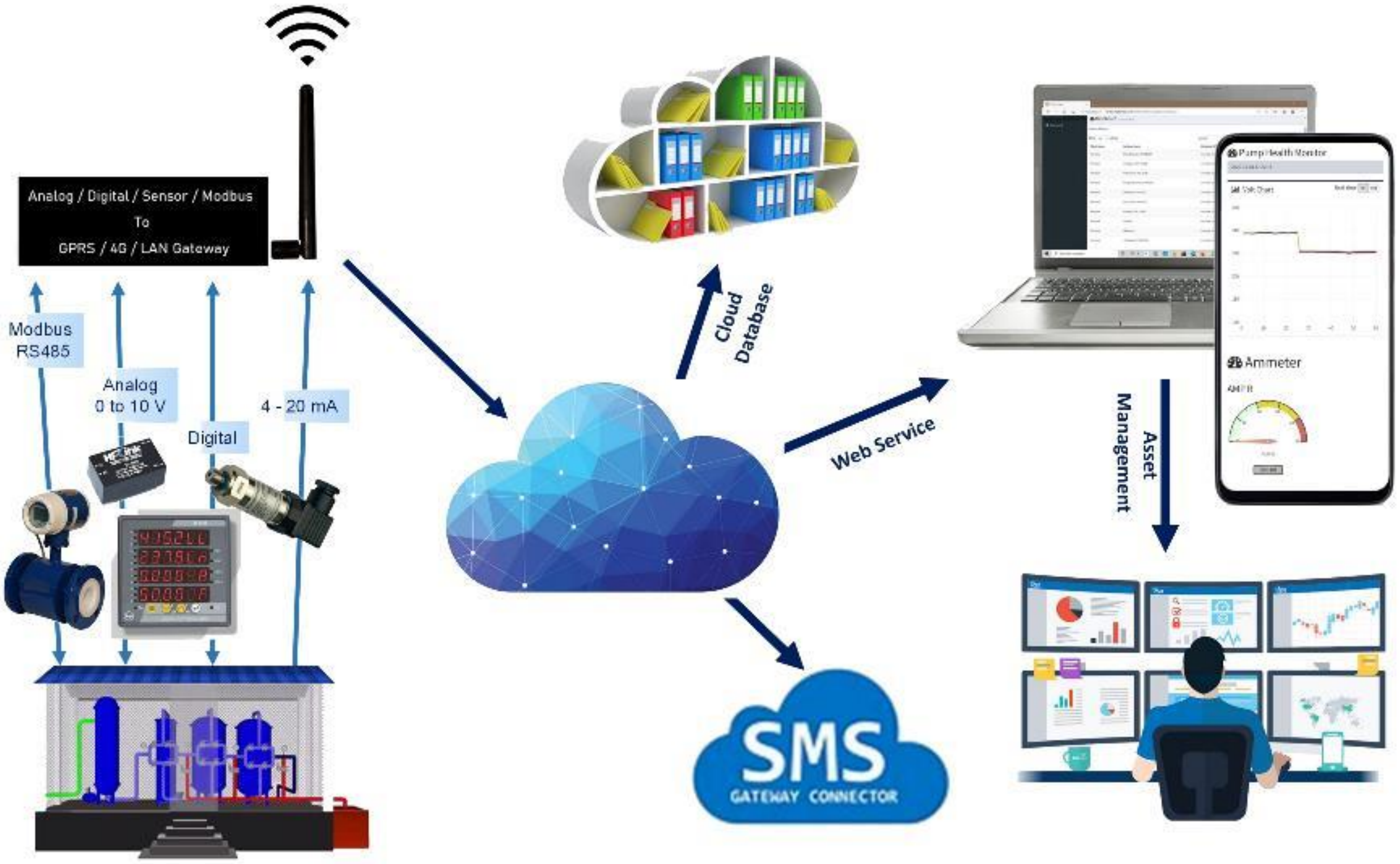
Ankit Nagar and T. Pradeep 14(2020). *ACS Nano*, 6420-6435

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

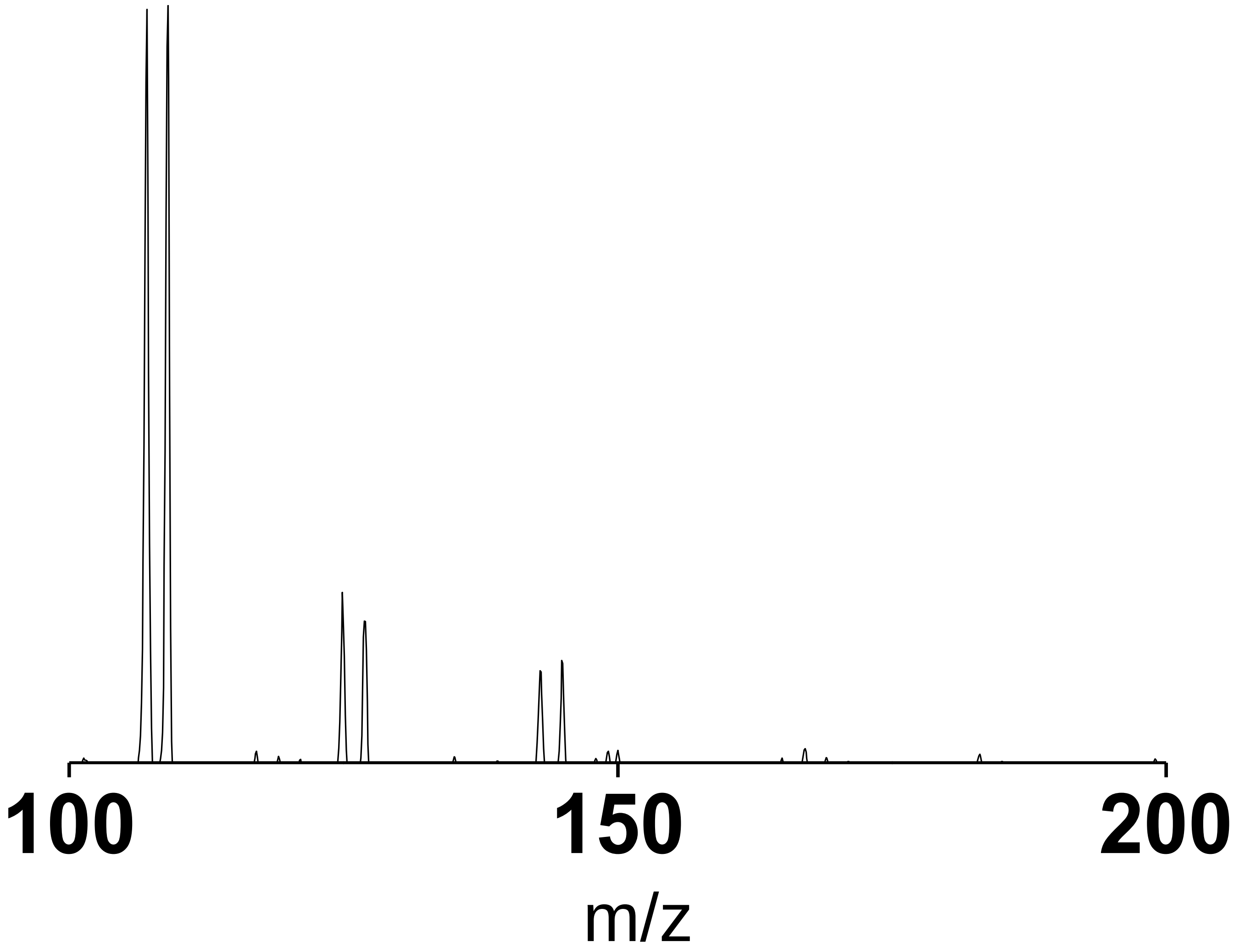
Now they are across the country

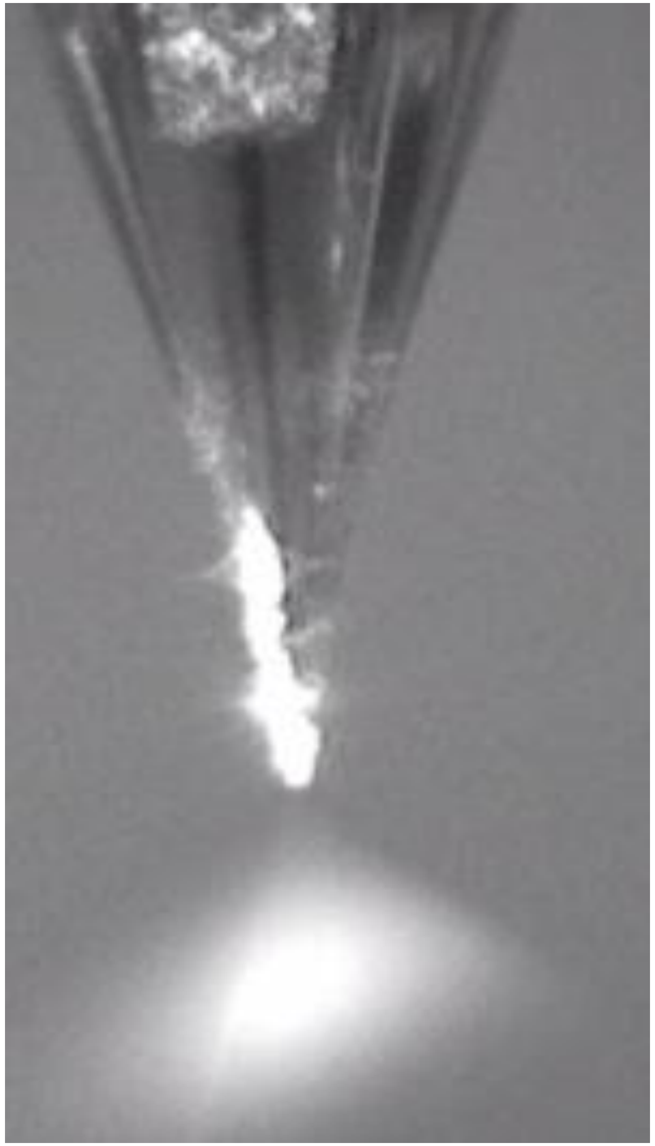
Components of IoT architecture implemented by DWSS, GoP



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

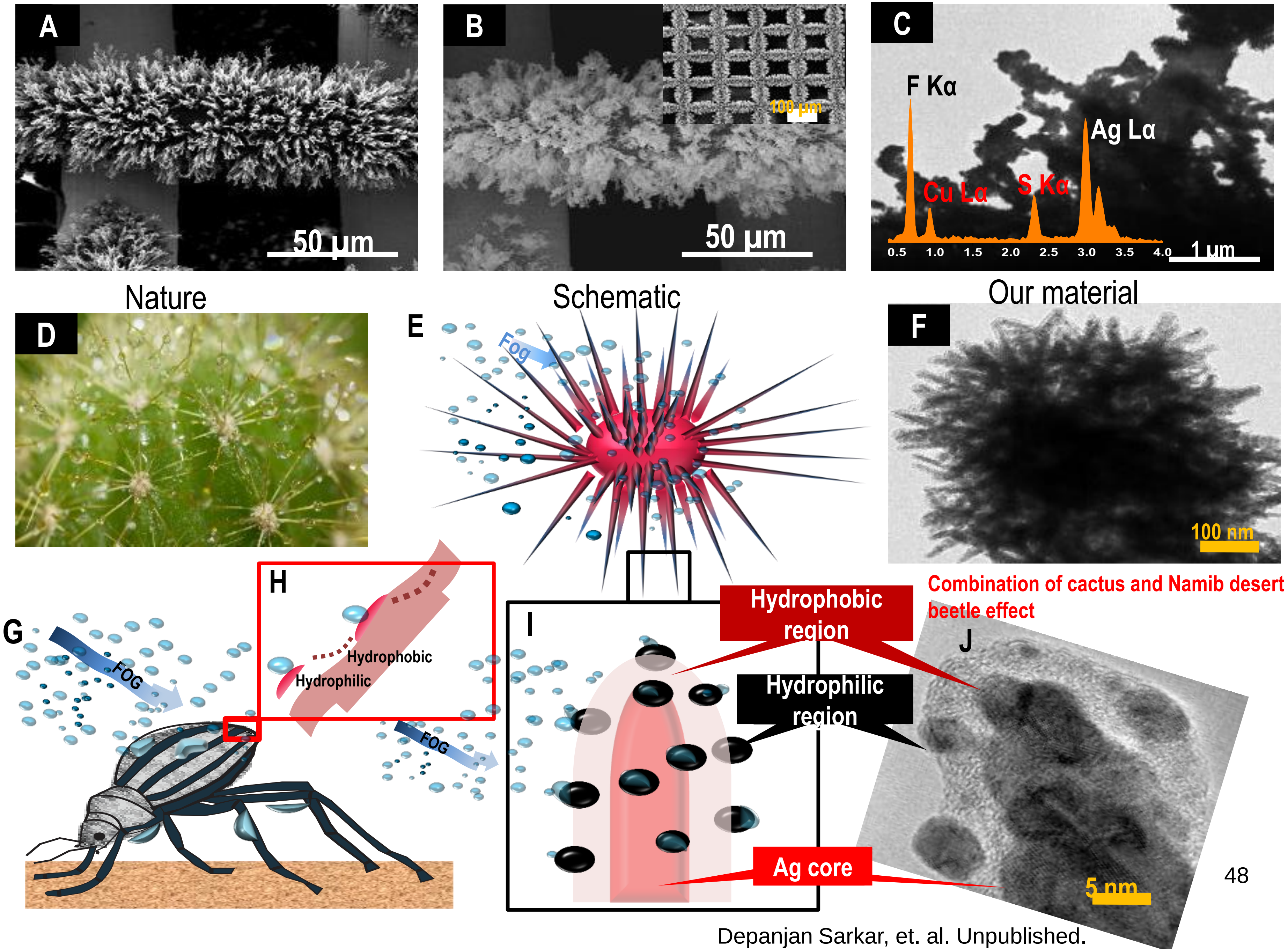
Atmospheric water harvesting



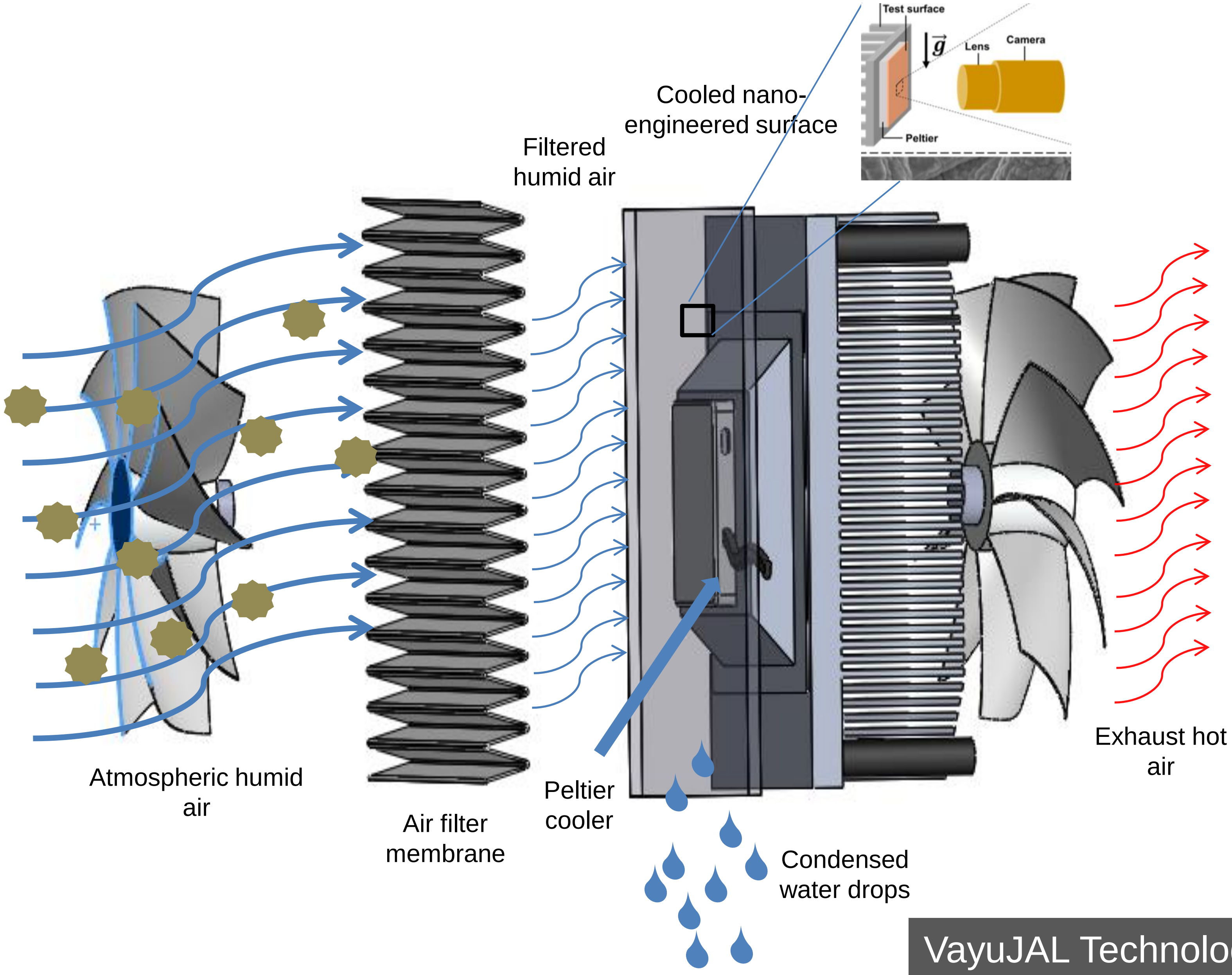


New harvesters

Depanjan Sarkar, et. al. *Advanced Materials*, 28 (11), 2016.



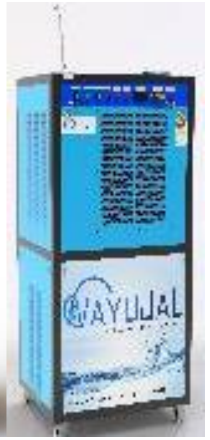
Depanjan Sarkar, et. al. Unpublished.



VayuJAL Technologies Pvt. Ltd.

Ramesh Kumar Soni and Ankit Nagar

Products in the field

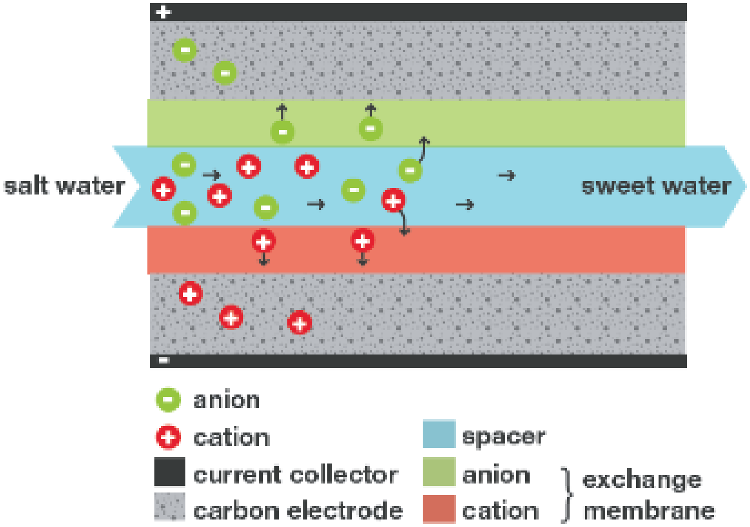


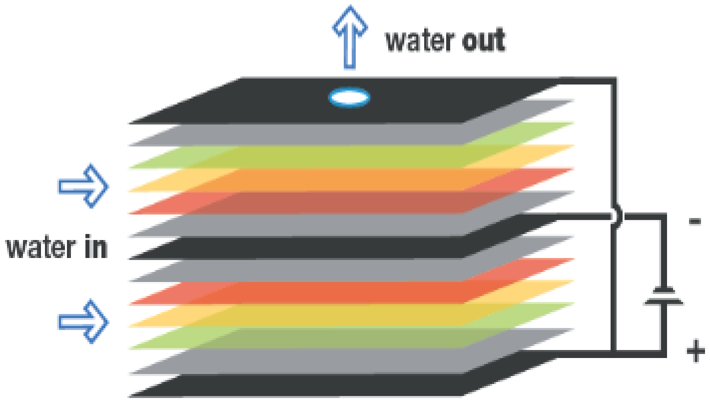
35 LPD   120 LPD   400 LPD   1000 LPD   2000 LPD

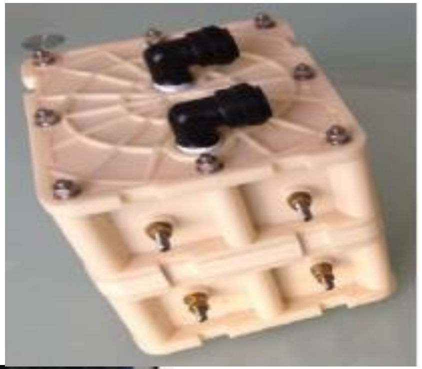
(LPD: Litres per day)

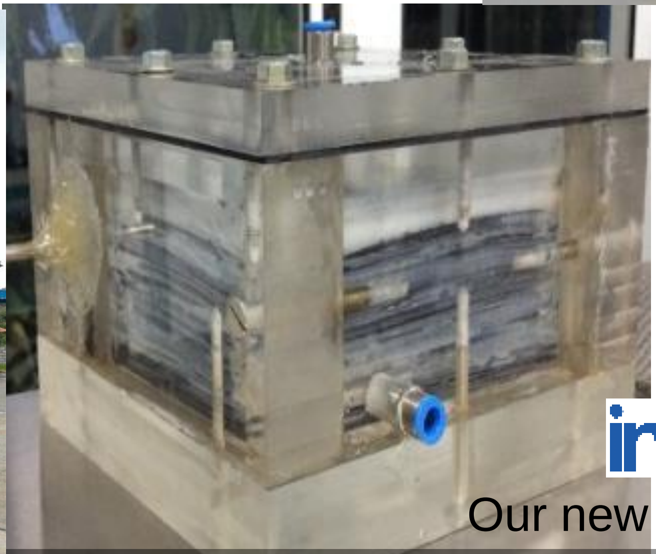
July 2023

Capacitive Desalination (CDI)





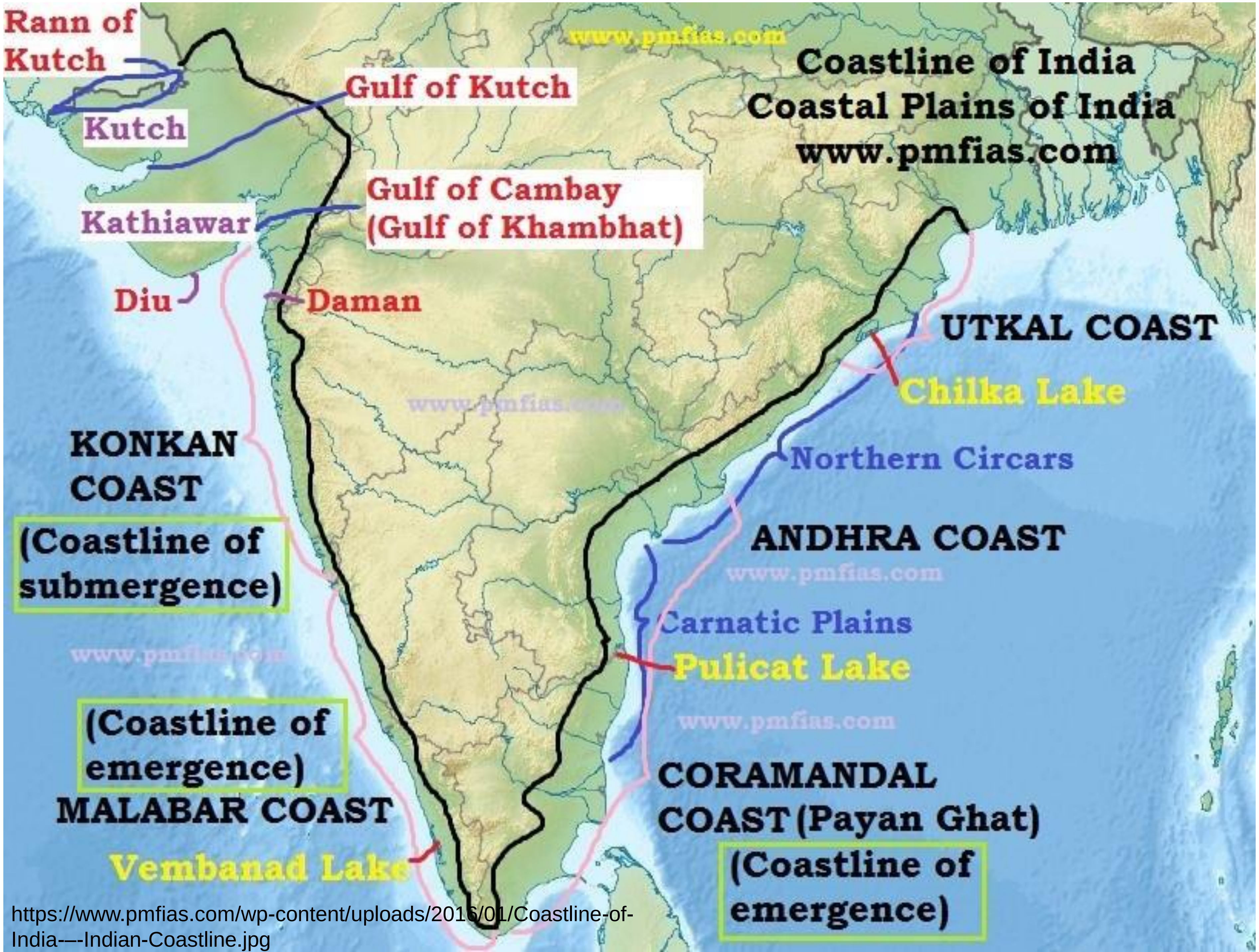




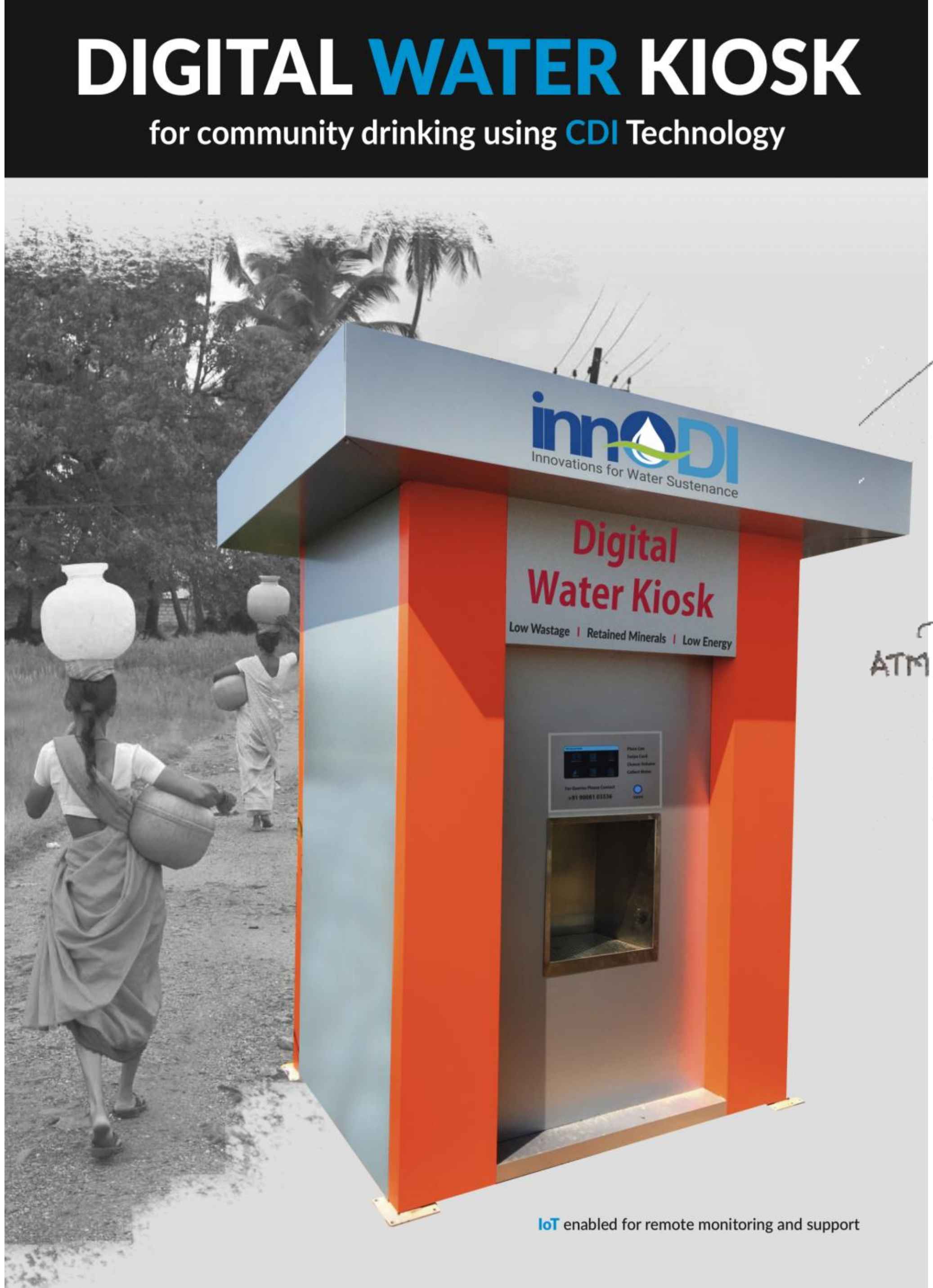
innoDI

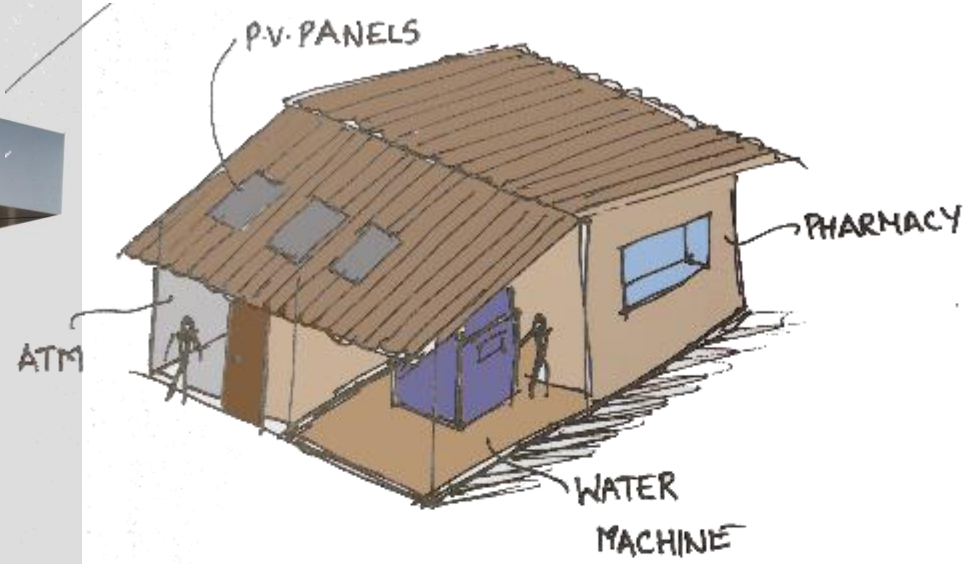
Our new company

Soujit Sengupta, Rabiul Islam and others



https://www.pmfias.com/wp-content/uploads/2016/01/Coastline-of-India-—-Indian-Coastline.jpg

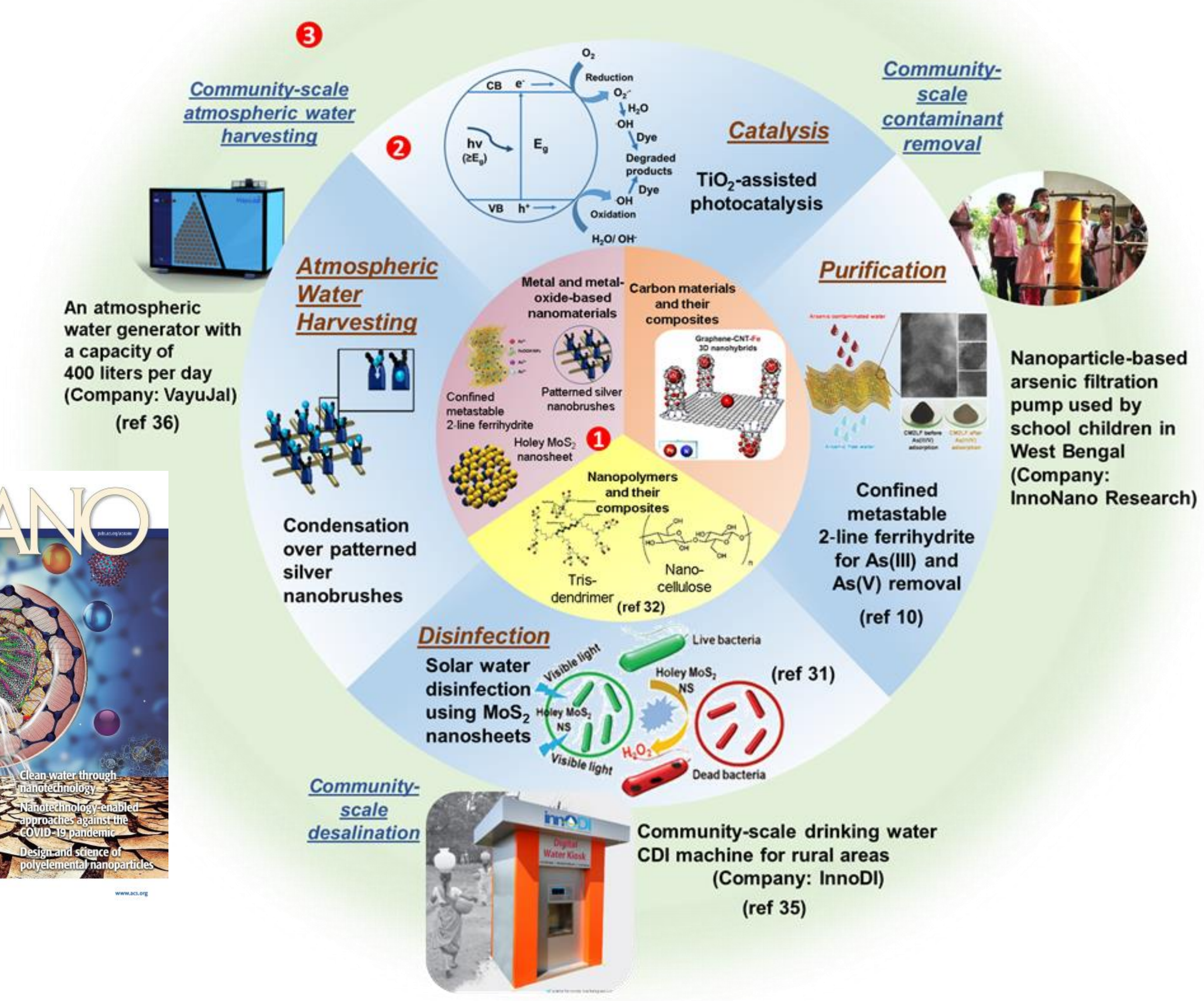


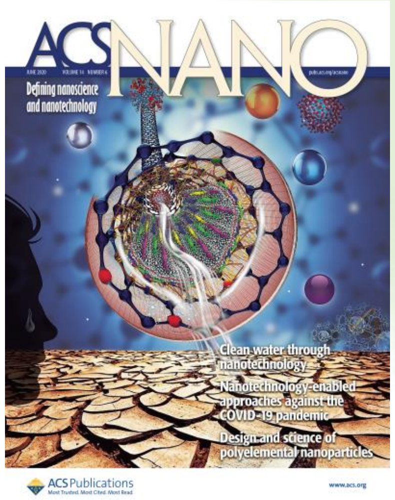


Products under implementation

Vijay Sampath and Tullio Servida

Evolution of materials to products



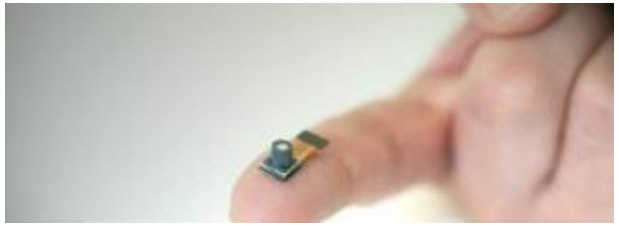


Ankit Nagar and T. Pradeep, *ACS Nano* 14 (2020) 6420-6435.

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)

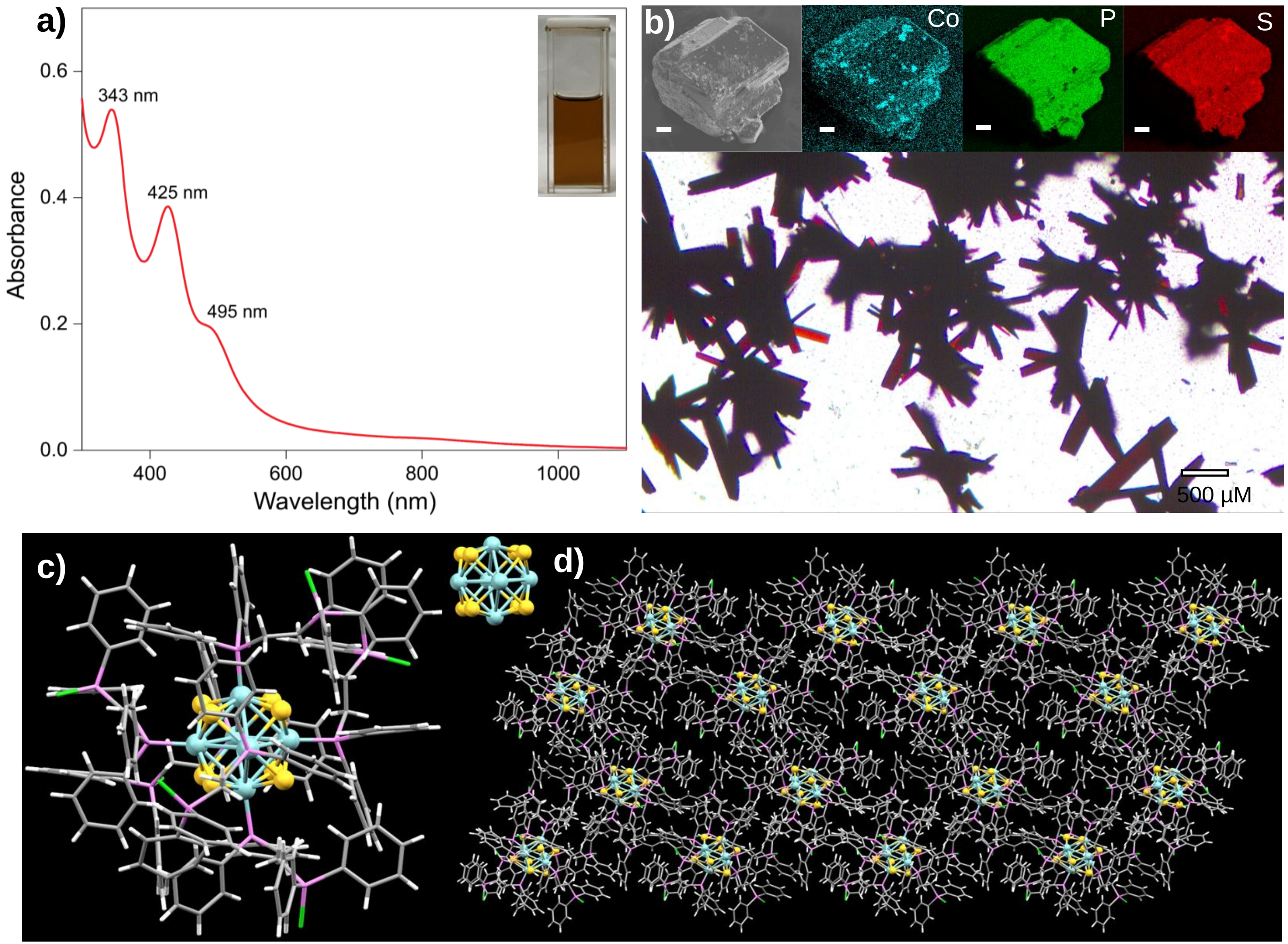


Water quality measurement – In the pipeline

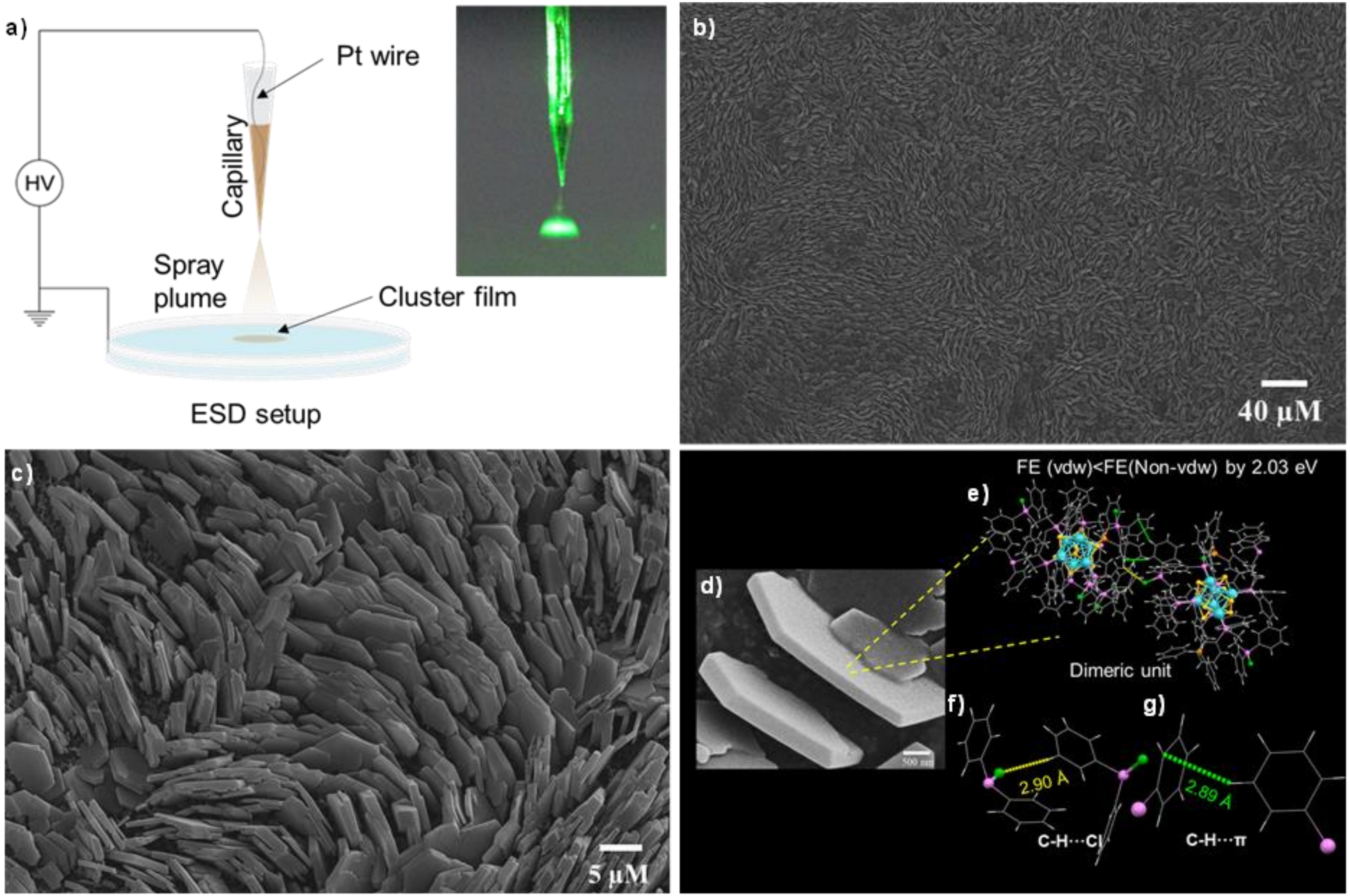
nanoλ

New electrodes - Aligned nanoplates of Co_6S_8

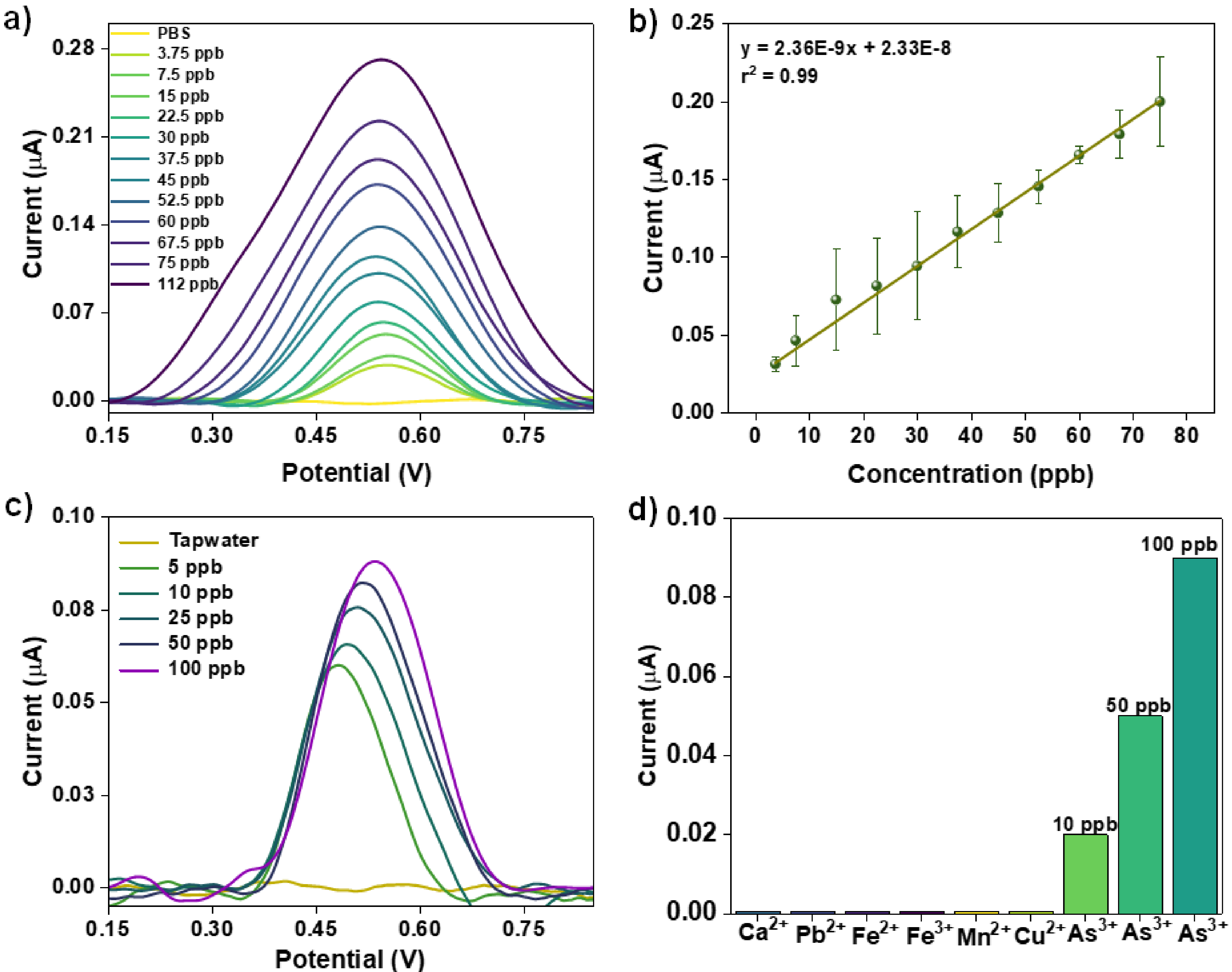
1,2-bis(diphenylphosphino)ethane (DPPE)



Electrospray deposition

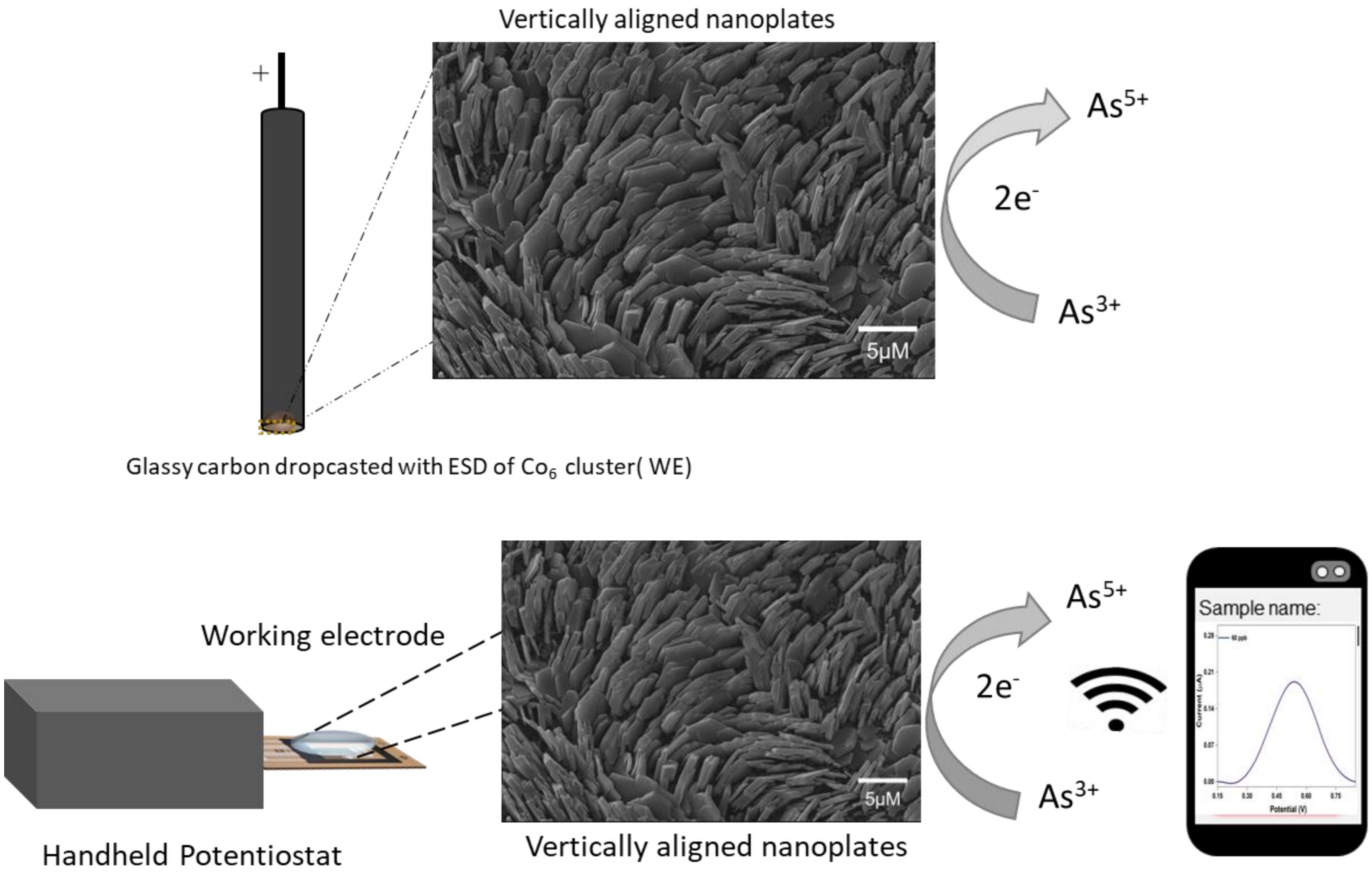


Sensing



a)
PBS
3.75 ppb
7.5 ppb
15 ppb
22.5 ppb
30 ppb
37.5 ppb
45 ppb
52.5 ppb
60 ppb
67.5 ppb
75 ppb
112 ppb
0.28
0.21
0.14
0.07
0.00
Current (µA)
0.15
0.30
0.45
0.60
0.75
Potential (V)
b)
y = 2.36E-9x + 2.33E-8
r2 = 0.99
0.25
0.20
0.15
0.10
0.05
0.00
Current (µA)
0
10
20
30
40
50
60
70
80
Concentration (ppb)
c)
Tapwater
5 ppb
10 ppb
25 ppb
50 ppb
100 ppb
0.10
0.08
0.05
0.03
0.00
Current (µA)
0.15
0.30
0.45
0.60
0.75
Potential (V)
d)
100 ppb
50 ppb
10 ppb
0.10
0.08
0.06
0.04
0.02
0.00
Current (µA)
Ca2+
Pb2+
Fe2+
Fe3+
Mn2+
Cu2+
As3+
As3+
As3+

Working electrode



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

Environmental Science & Technology Letters

pubs.acs.org/journal/estlcu

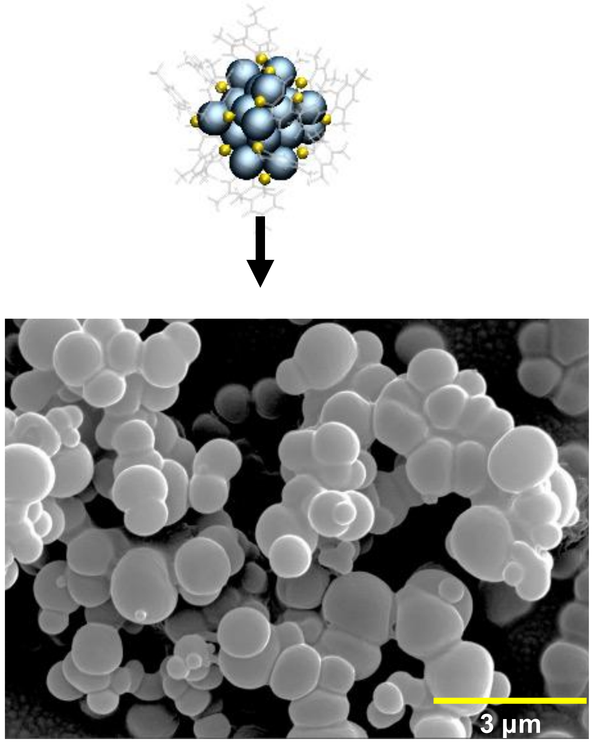
Letter

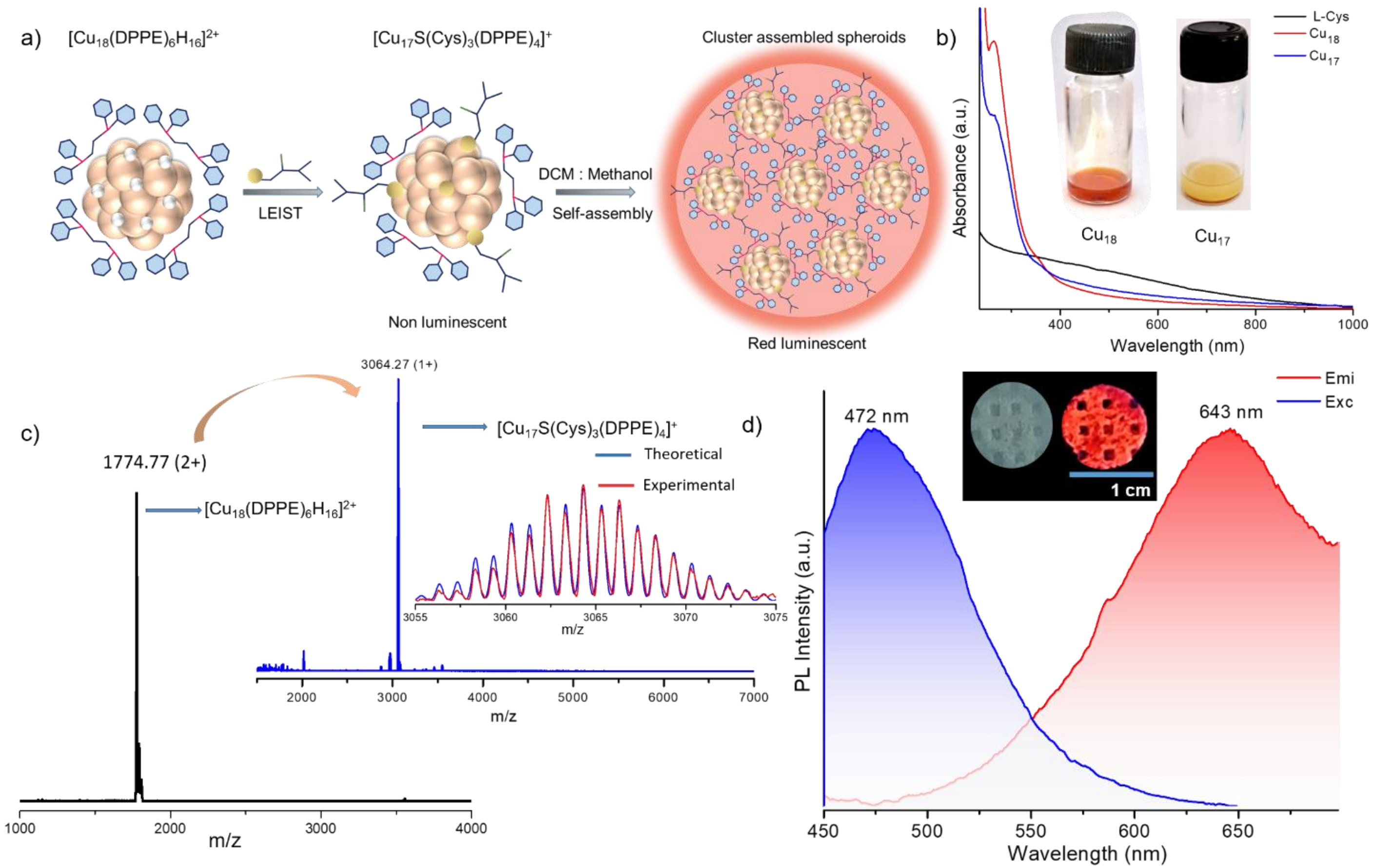
Cysteine-Protected Antibacterial Spheroids of Atomically Precise Copper Clusters for Direct and Affordable Arsenic Detection from Drinking Water

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

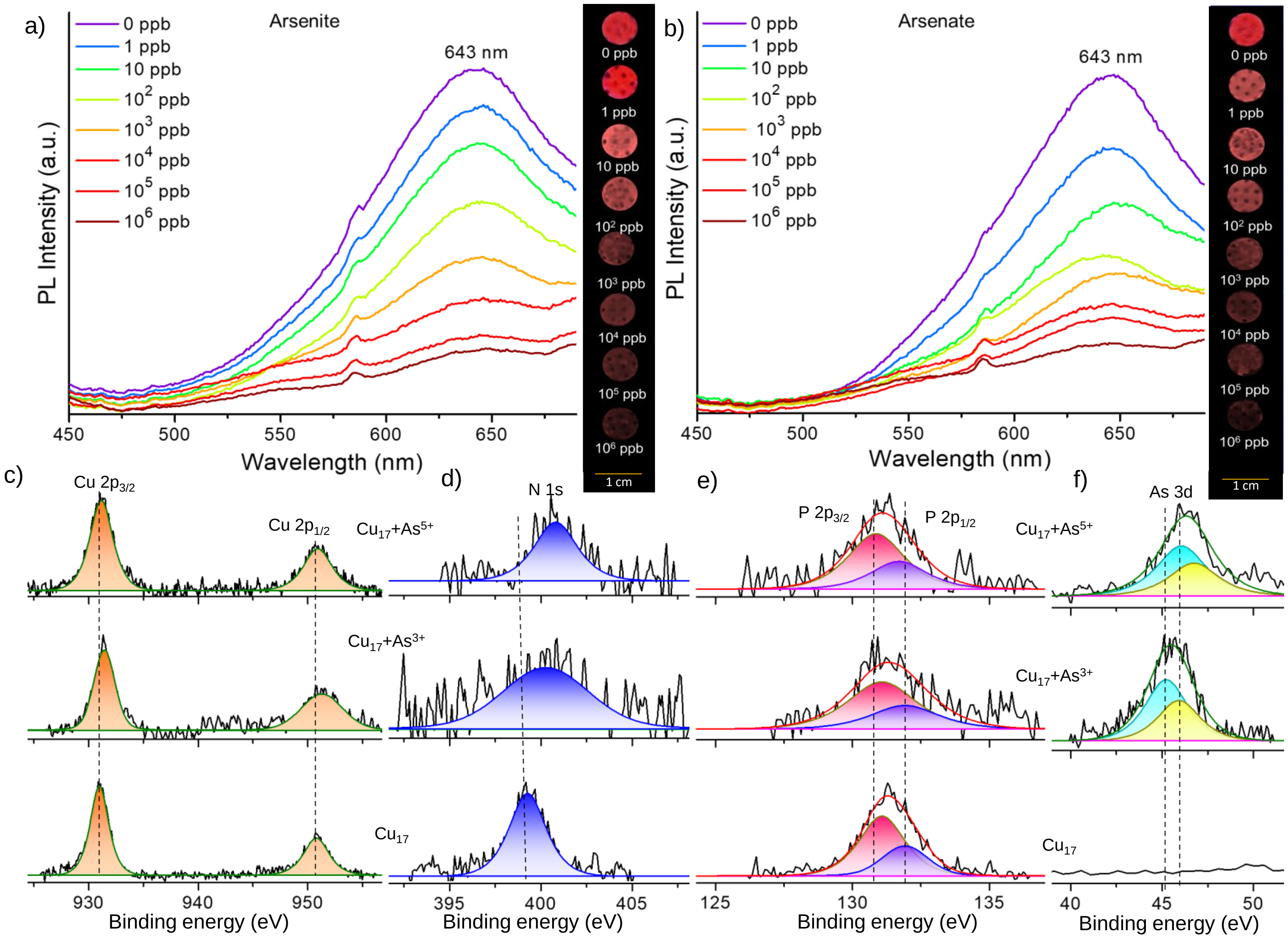
Cite This: https://doi.org/10.1021/acs.estlett.4c00264

Read Online

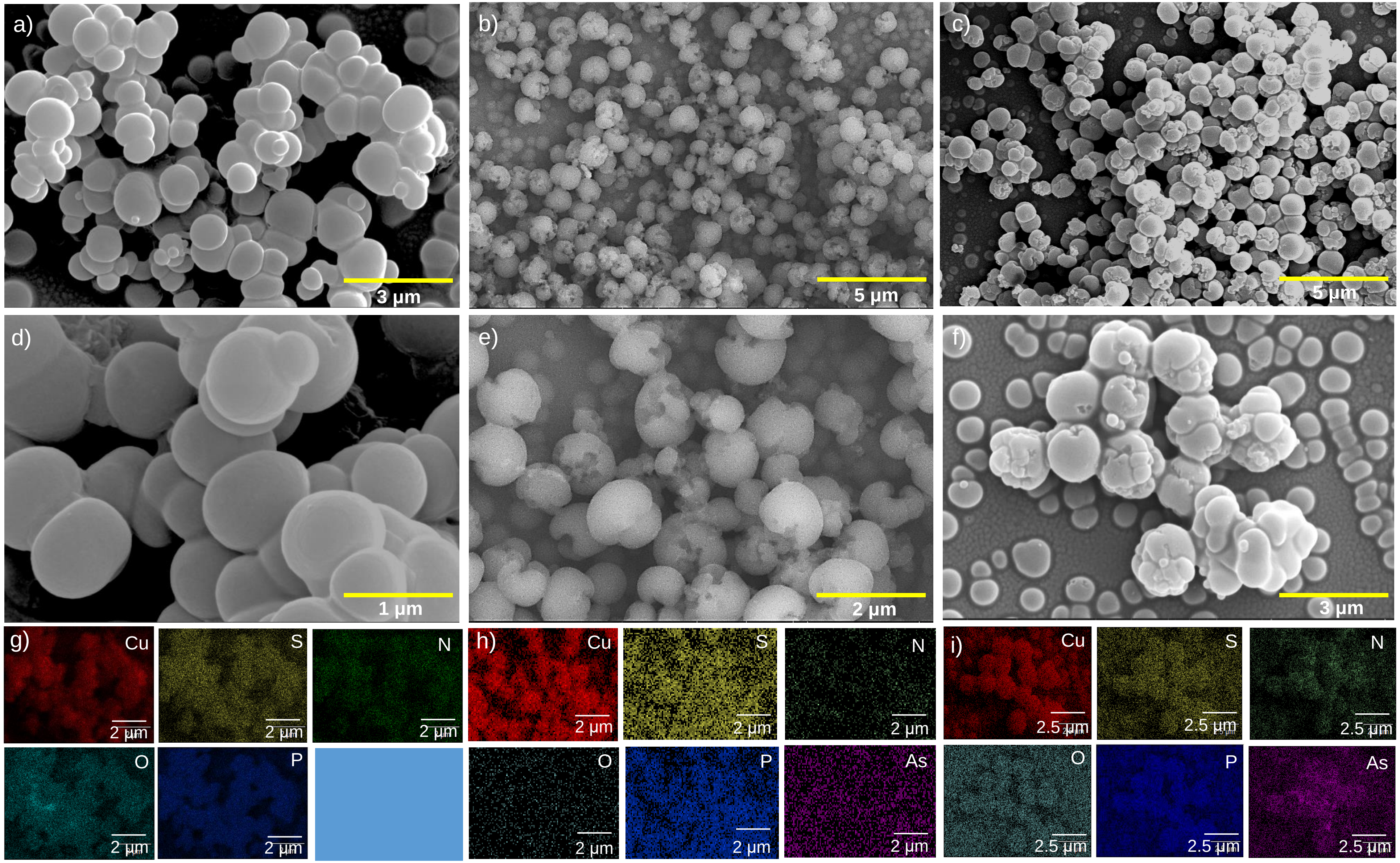




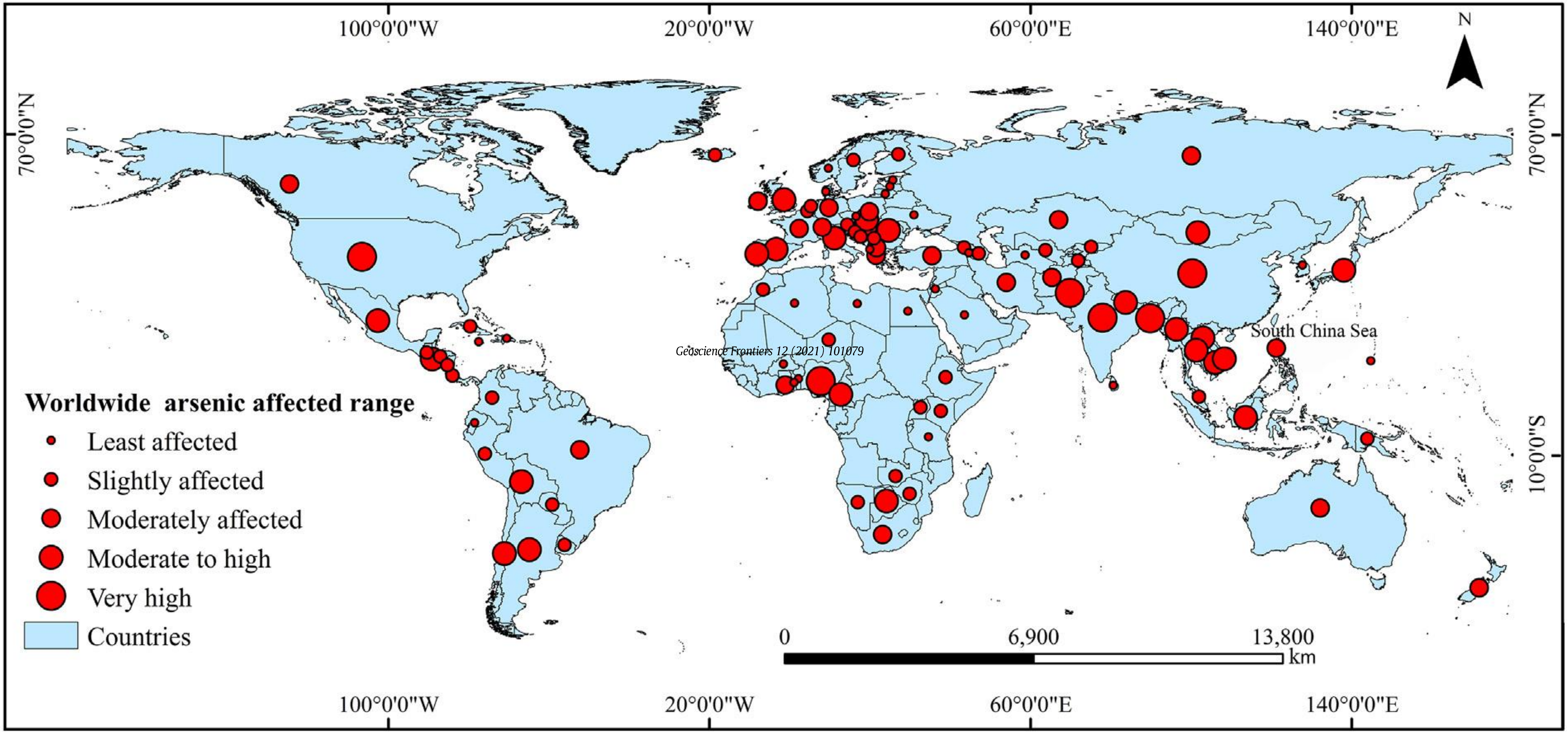
J. S. Kumar, *Environ. Sci. Technol. Lett.* 2024, 11, 8, 831–837.



a)
Arsenite
0 ppb
1 ppb
10 ppb
10^2 ppb
10^3 ppb
10^4 ppb
10^5 ppb
10^6 ppb
643 nm
PL Intensity (a.u.)
Wavelength (nm)
1 cm
b)
Arsenate
c)
Cu 2p3/2
Cu 2p1/2
d)
N 1s
e)
P 2p3/2
P 2p1/2
f)
As 3d
Cu17+As5+
Cu17+As3+
Cu17
Binding energy (eV)

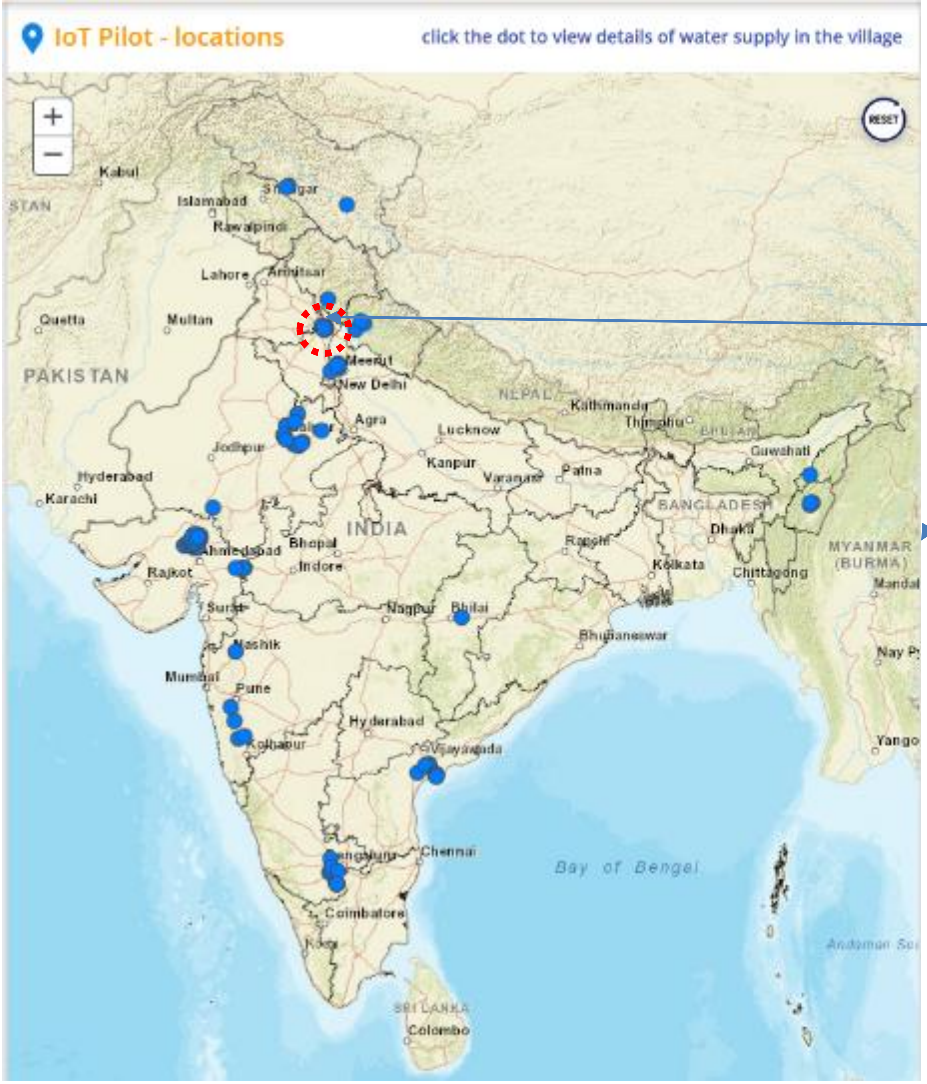

a)
3 µm
b)
5 µm
c)
5 µm
d)
1 µm
e)
2 µm
f)
3 µm
g)
Cu
2 µm
S
2 µm
N
2 µm
O
2 µm
P
2 µm
h)
Cu
2 µm
S
2 µm
N
2 µm
O
2 µm
P
2 µm
As
2 µm
i)
Cu
2.5 µm
S
2.5 µm
N
2.5 µm
O
2.5 µm
P
2.5 µm
As
2.5 µm

Arsenic poisoning across the world



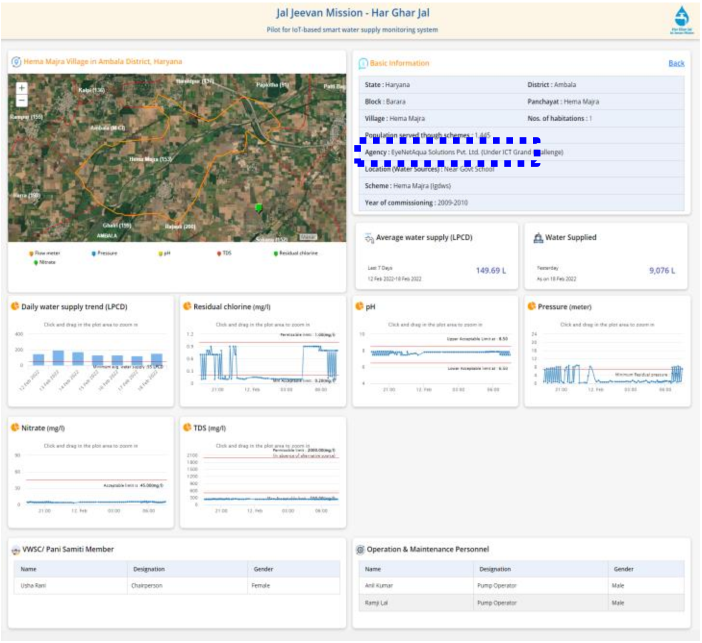
E. Shaji, M. Santosh, K. V. Sarath, Pranav Prakash, V. Deepch and B. V. Divya, Geoscience Frontiers, 12 (2021) 101079.

India’s water is being monitored



IITM/IISc

Installations made by four companies



Can Water Microdroplets Make Soil?

A path to sustainable nanotechnology

Science

NANOPARTICLES

Spontaneous weathering of natural minerals in charged water microdroplets forms nanomaterials

B. K. Spoorthi[1], Koyendrila Debnath[2], Pallab Basuri[1], Ankit Nagar[1], Umesh V. Waghmare[2], Thalappil Pradeep[1,3*]

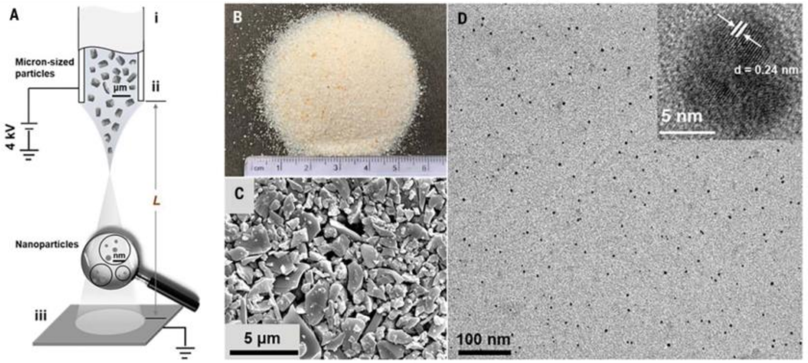
In this work, we show that particles of common minerals break down spontaneously to form nanoparticles in charged water microdroplets within milliseconds. We transformed micron-sized natural minerals like quartz and ruby into 5- to 10-nanometer particles when integrated into aqueous microdroplets generated via electrospray. We deposited the droplets on a substrate, which allowed nanoparticle characterization. We determined through simulations that quartz undergoes proton-induced slip, especially when reduced in size and exposed to an electric field. This leads to particle scission 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.

Nanoparticles of minerals exist naturally in soil, and some of them are essential for life (1). Microdroplets have been a topic of interest over the past decade, and the confined environment within them is known to cause chemical synthesis at an accelerated rate, as well as other processes such as the formation of nanoparticles (2). We decided to explore whether natural minerals could disintegrate in microdroplets, through a process opposite to chemical synthesis.

For our experiments, we prepared micron-scale particles of natural quartz (SiO_2) and ruby (Cr-substituted Al_2O_3) for use in an electrospray setup (Fig. 1, A and B). We ground commercial millimeter-sized quartz particles well using a mortar and pestle and used centrifugation to separate the differently sized particles that formed. We carefully excluded all the particles smaller than 1 mm in size and used particles of 5 to 10 mm that were suspended in water for the experiment (Fig. 1C). Even after ultrasonication to detach any adhered particles, we found some smaller particles attached to a few larger ones (Fig. 1C). These adhering particles had dimensions greater than 100 nm (fig. S1). We took an optical image of the ground quartz powder and an optical microscopic image of the separated particles that we used for electrospray (fig. S2). We electrosprayed a suspension of about 0.1 mg/ml of the separated quartz particles through a capillary tube that had an inner diameter of 50 mm ... flow rate of 0.5 ml/hour and observed the resulting plume (Fig. 1A). We collected the product of electrospray 1.5 cm away from the spray tip, which resulted in a flight time on the order of 10 ms, consistent with similar experiments (3, 4). The product that was deposited on a transmission electron microscopy (TEM) grid had only 5- to 10-nm-diameter particles (Fig. 1D) throughout the grid. Under higher magnification, particles of different morphologies were observed. The particles showed the (110) plane of quartz (inset of Fig. 1D). Sonication had no effect on the breaking of silica particles. Experimental methods are presented in the supplementary materials, including a video of the electrospray process (movie S1).

To ensure that our initial observations were truly representative of the process, we performed measurements on larger quantities of samples. We built a multinozzle electrospray unit composed of six nozzles. We electrosprayed 1 liter of the suspension that contained 100 mg of the crushed micron-sized particles discontinuously over a month at the optimized conditions (spray voltage and distance) and a 3 ml/hour flow rate, and a deposit

[1]Department of Chemistry, Indian Institute of Technology Madras, Chennai 600036, India. [2]Theoretical Sciences Unit, Jawaharlal Nehru Centre for Advanced Scientific Research, Bangalore 560064, India. [3]International Centre for Clean Water, IIT Madras Research Park, Chennai 600113, India.
*Corresponding author. Email: pradeep@iitm.ac.in



Spoorthi et al., Science 384, 1012–1017 (2024) 31 May 2024

A scale of 1000

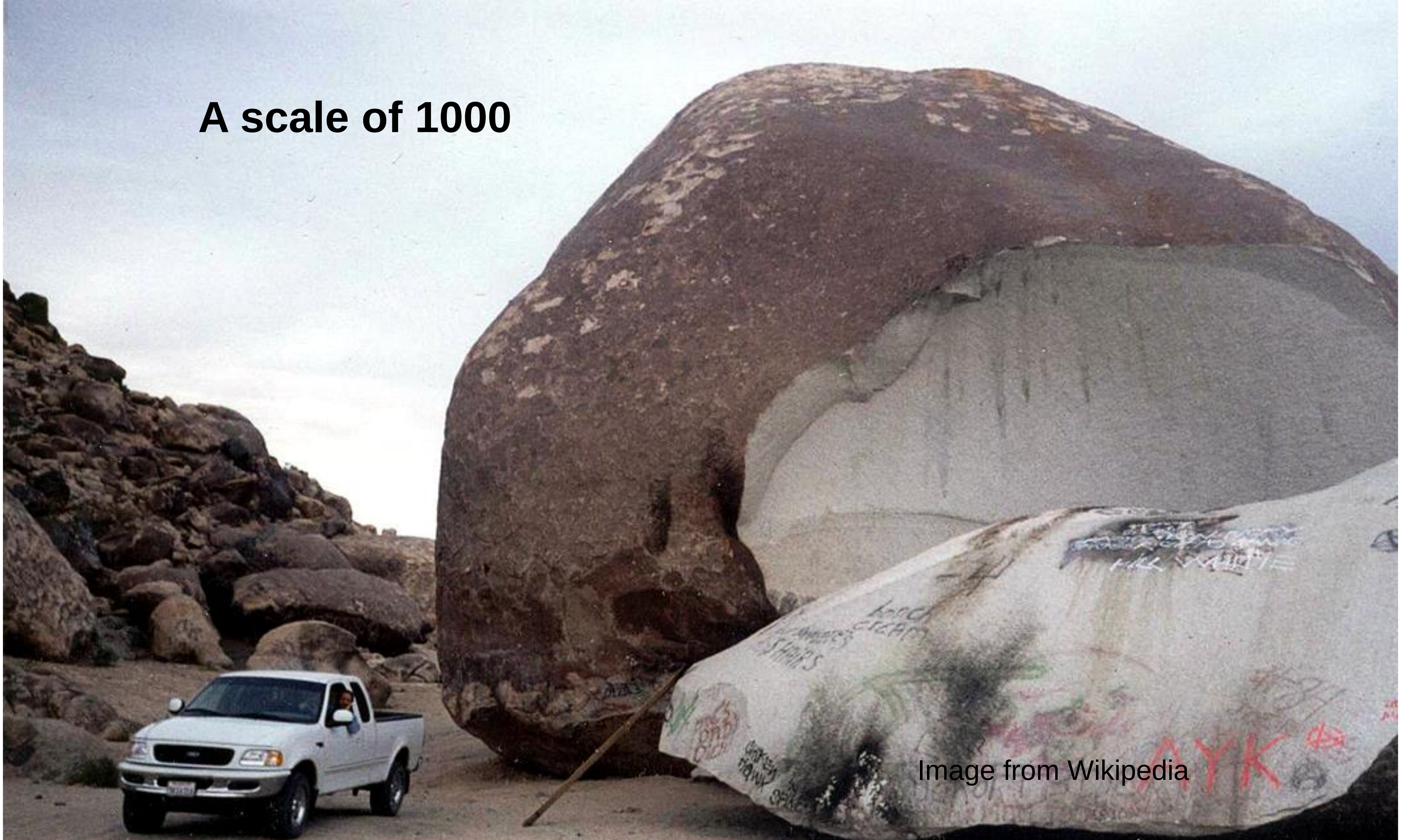
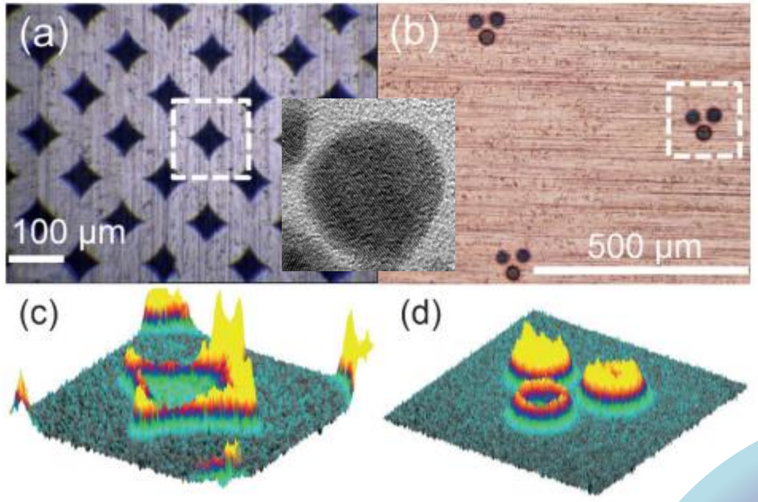
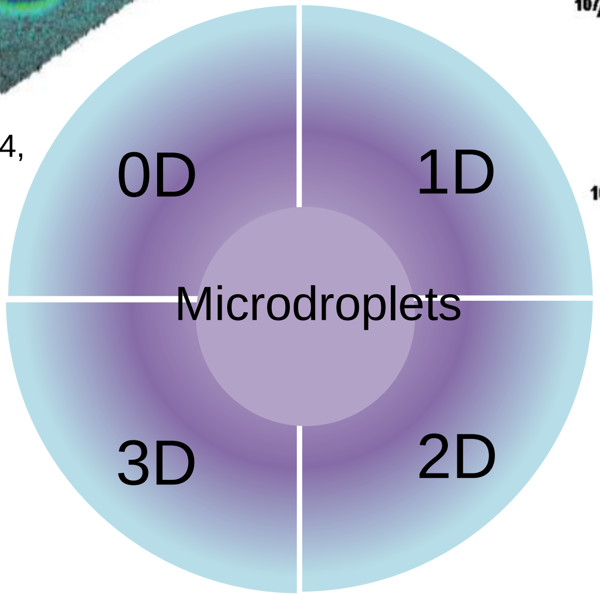


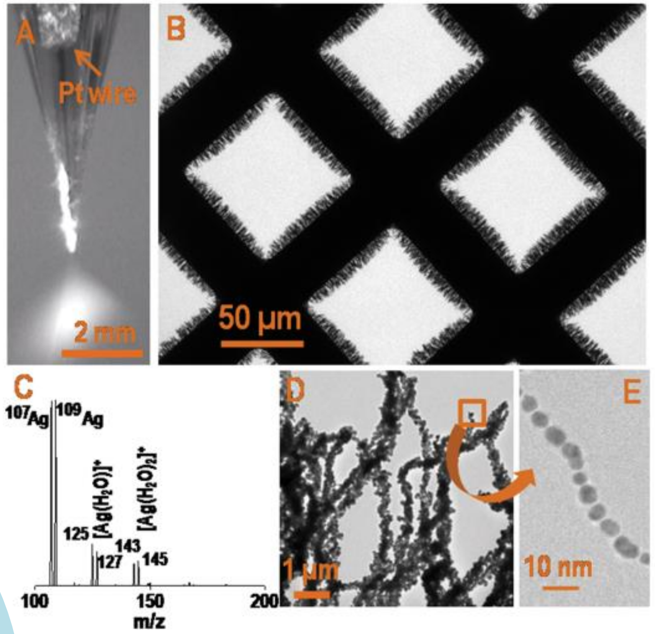
Image from Wikipedia

Functional Nanomaterials

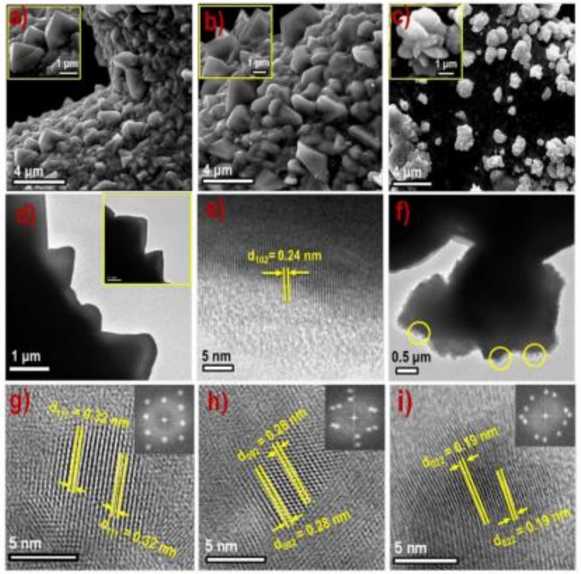


Anyin Li, et. al., Angew. Chem. Int. Ed. 2014, 53, 12528 –12531.

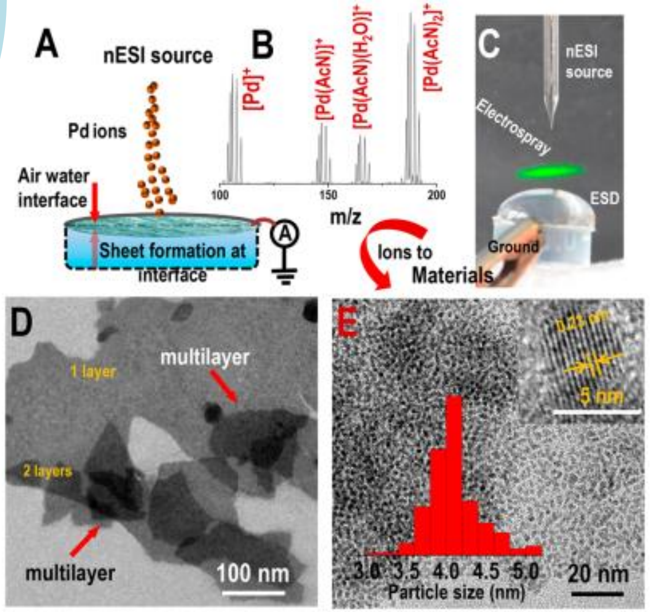




Depanjan Sarkar et. al., *Adv. Mater.* 2016, 28, 2223–2228.



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



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

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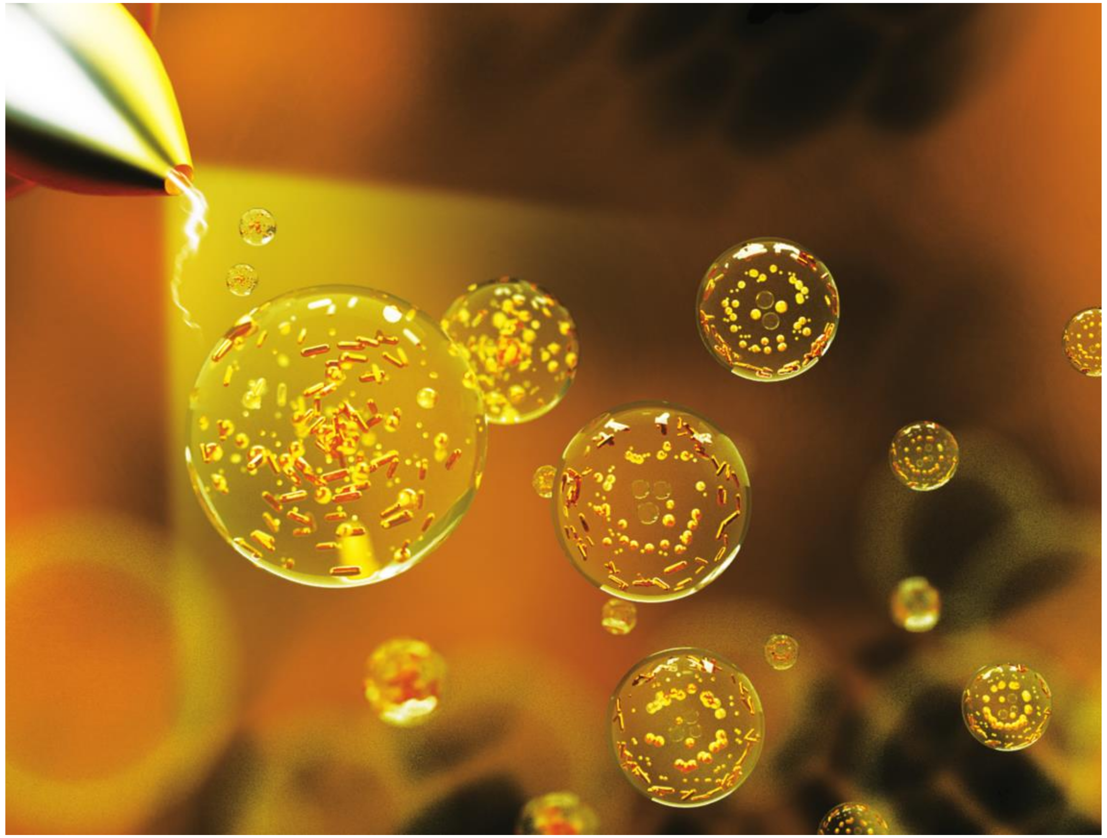
Number 45
7 December 2022
Pages 13251–13634

Chemical Science

rsc.li/chemical-science

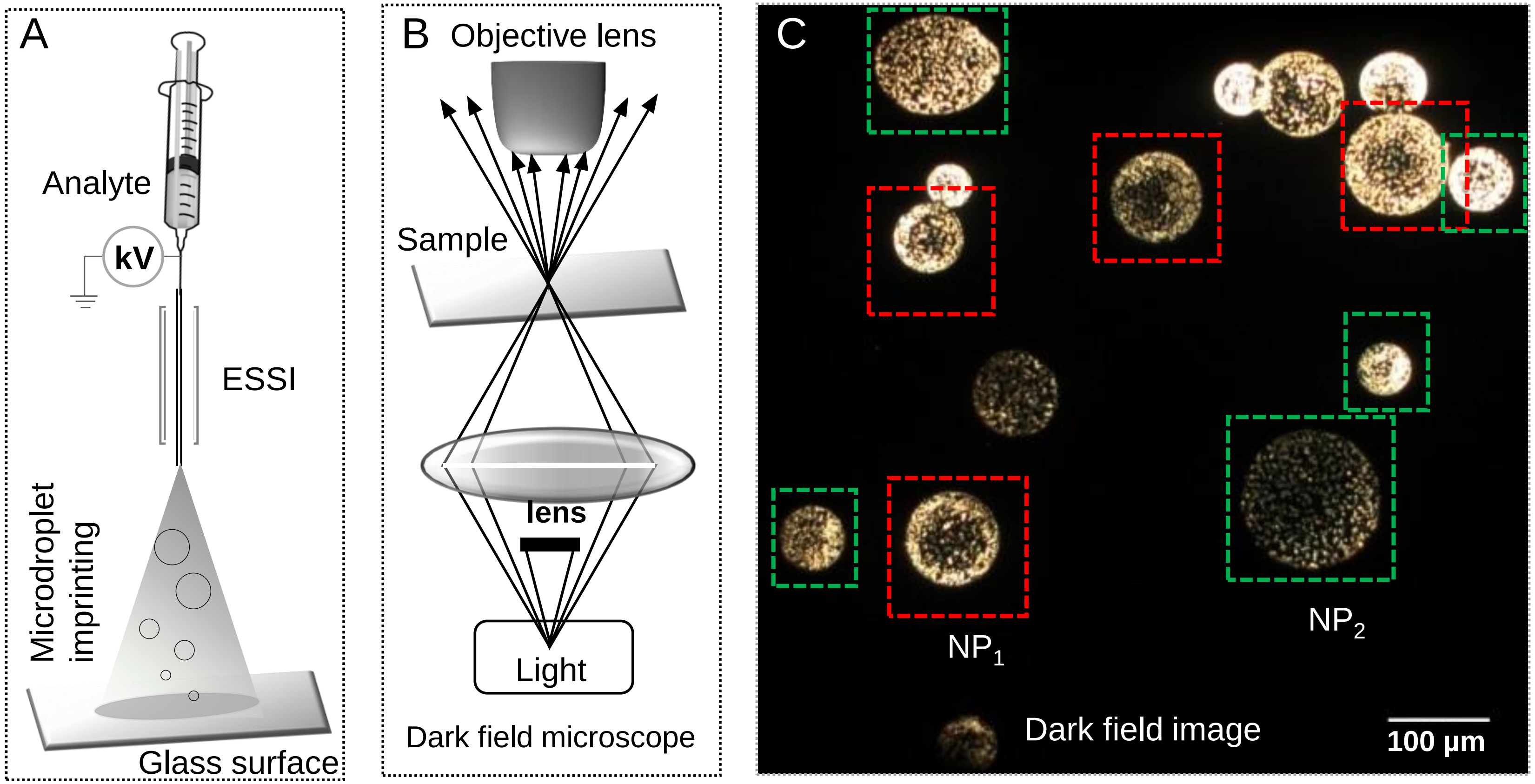


ISSN 2041-6539

ROYAL SOCIETY OF CHEMISTRY

EDGE ARTICLE
Thalappil Pradeep *et al.*
Spatial reorganization of analytes in charged aqueous microdroplets

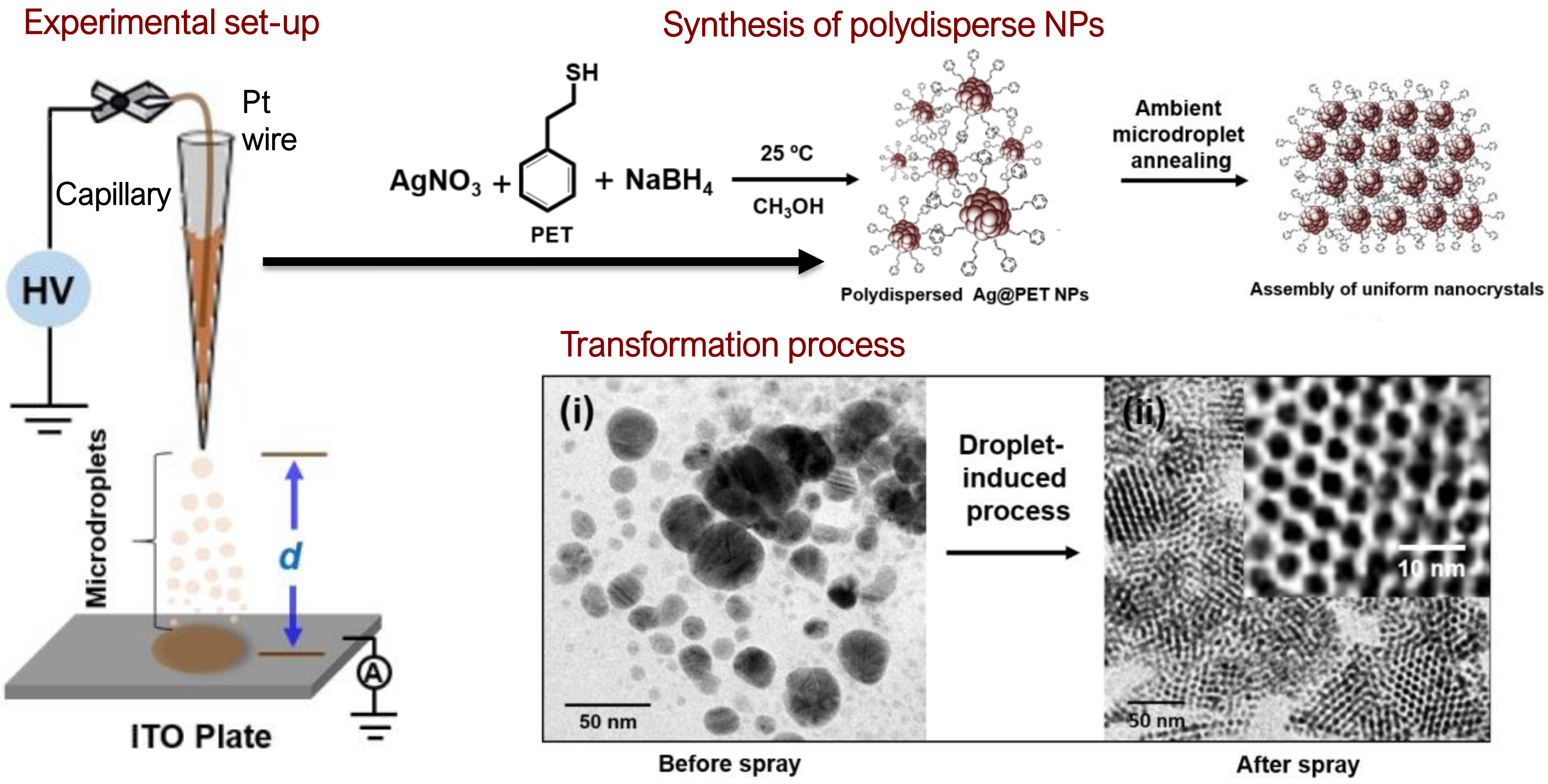
Understanding Microdroplets



Pallab Basuri et. al. *Chem. Sci.,* 2022, 13, 13321–13329.

Transformation of Materials in Microdroplets

Ambient Microdroplet Annealing of Nanoparticles



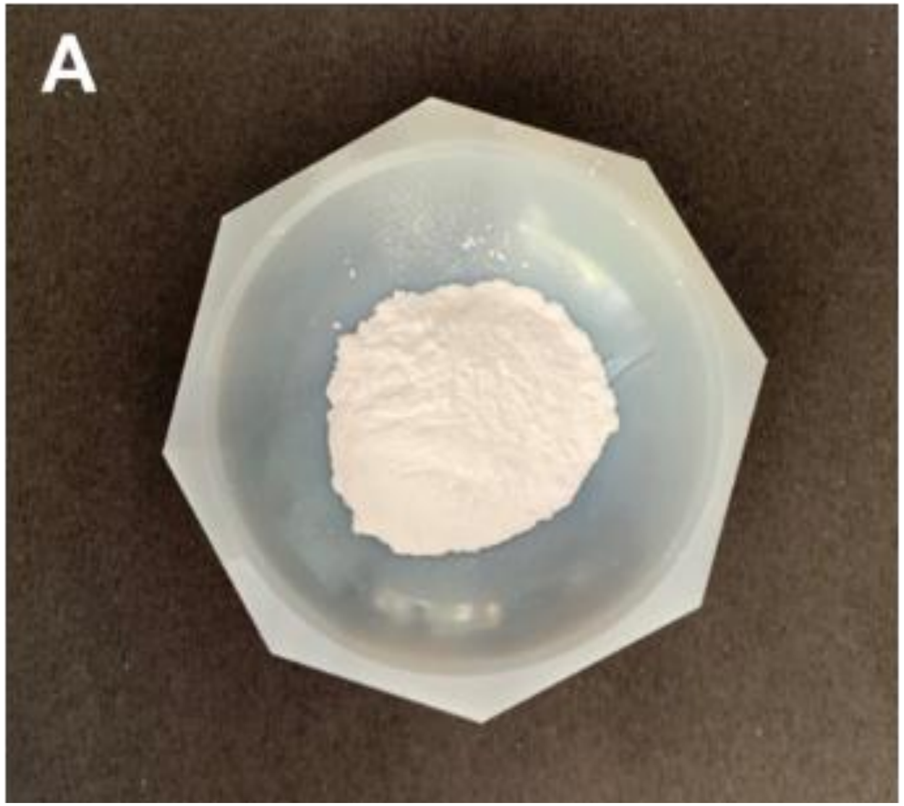
Angshuman Ray Chowdhuri et. al., *Chem. Sci.*, 2021, 12, 6370–6377.

Thanks to ChatGPT

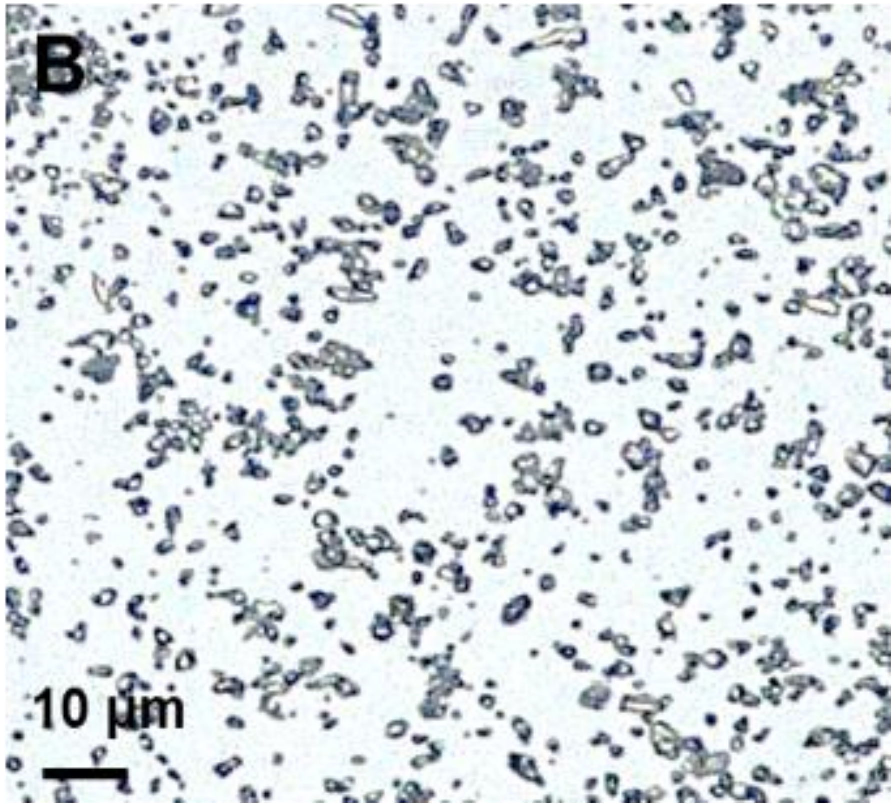
Weathering in Nature

Sand, the Ubiquitous Material

Images from Wikipedia

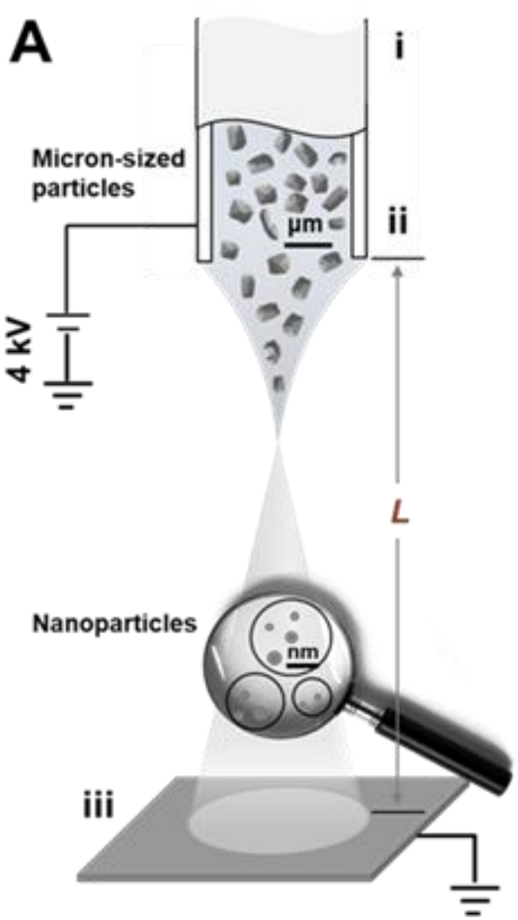


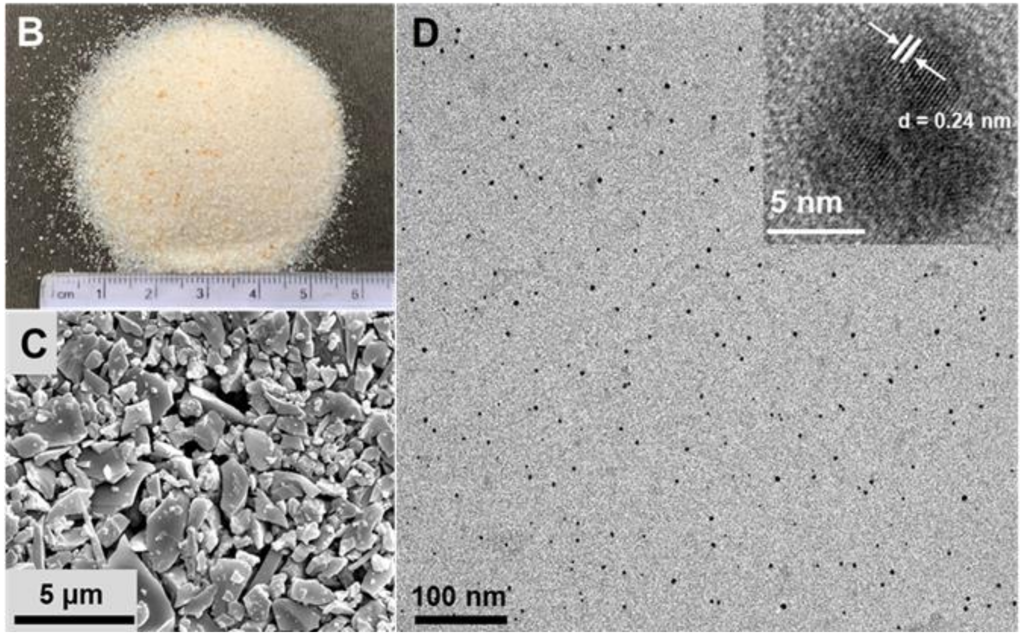
Ground silica



Optical image of silica

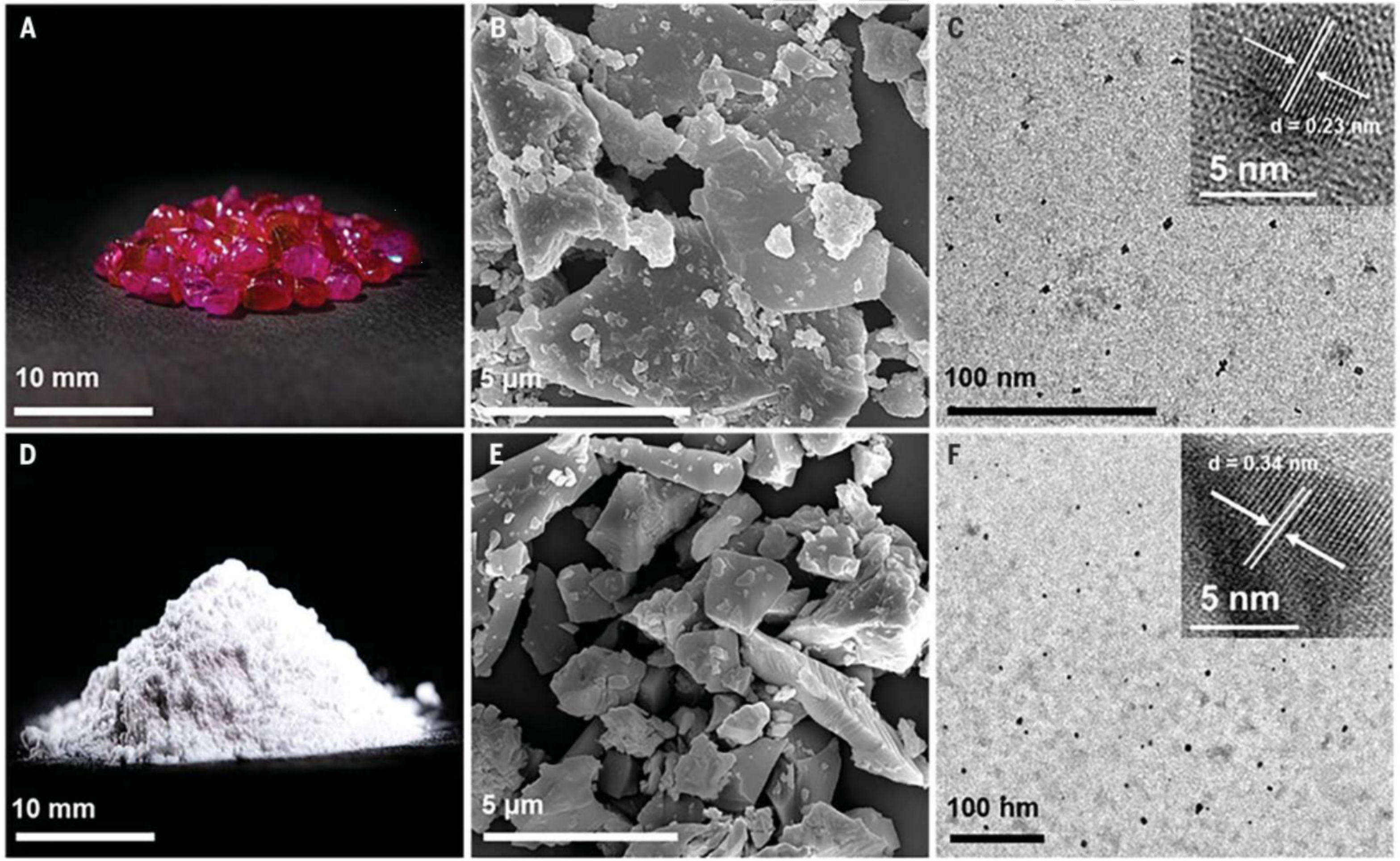
Weathering of Minerals in Microdroplets



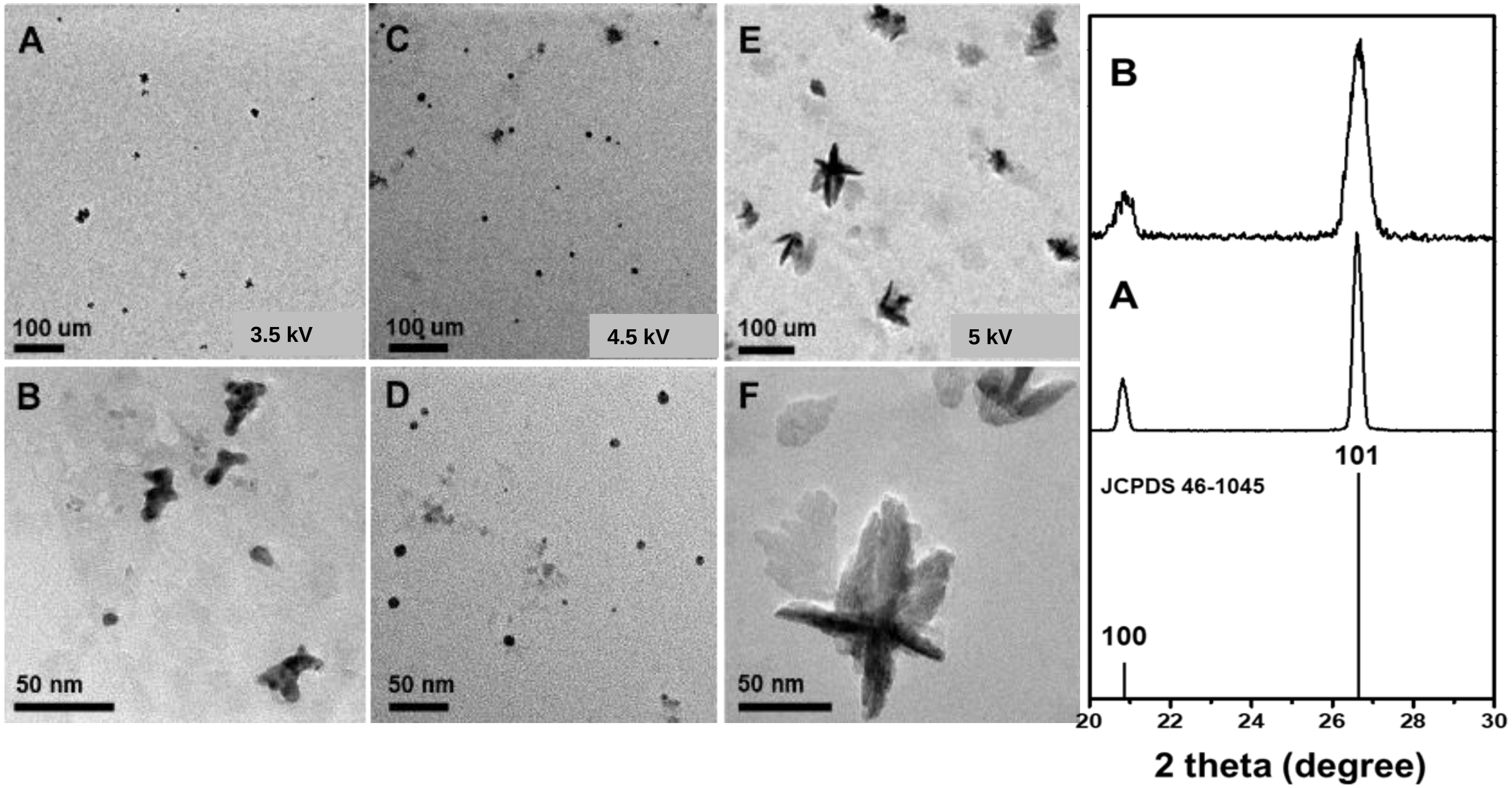


Spoorthi, et. al., *Science*, 2024

Ruby, Fused Alumina



Fragmentation of Silica – Varying Conditions

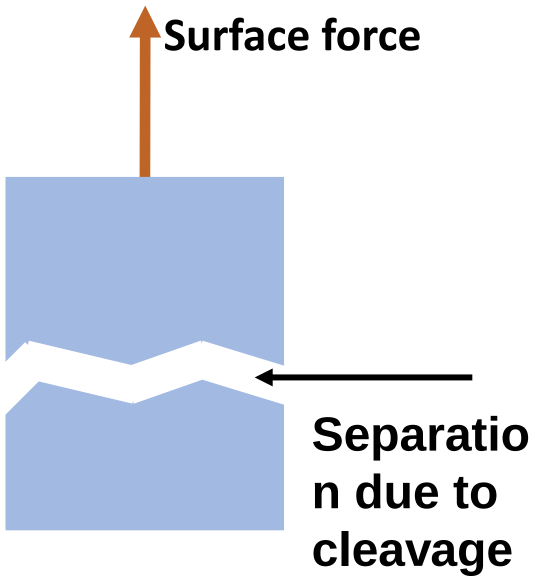


SiO_2 after electrospray

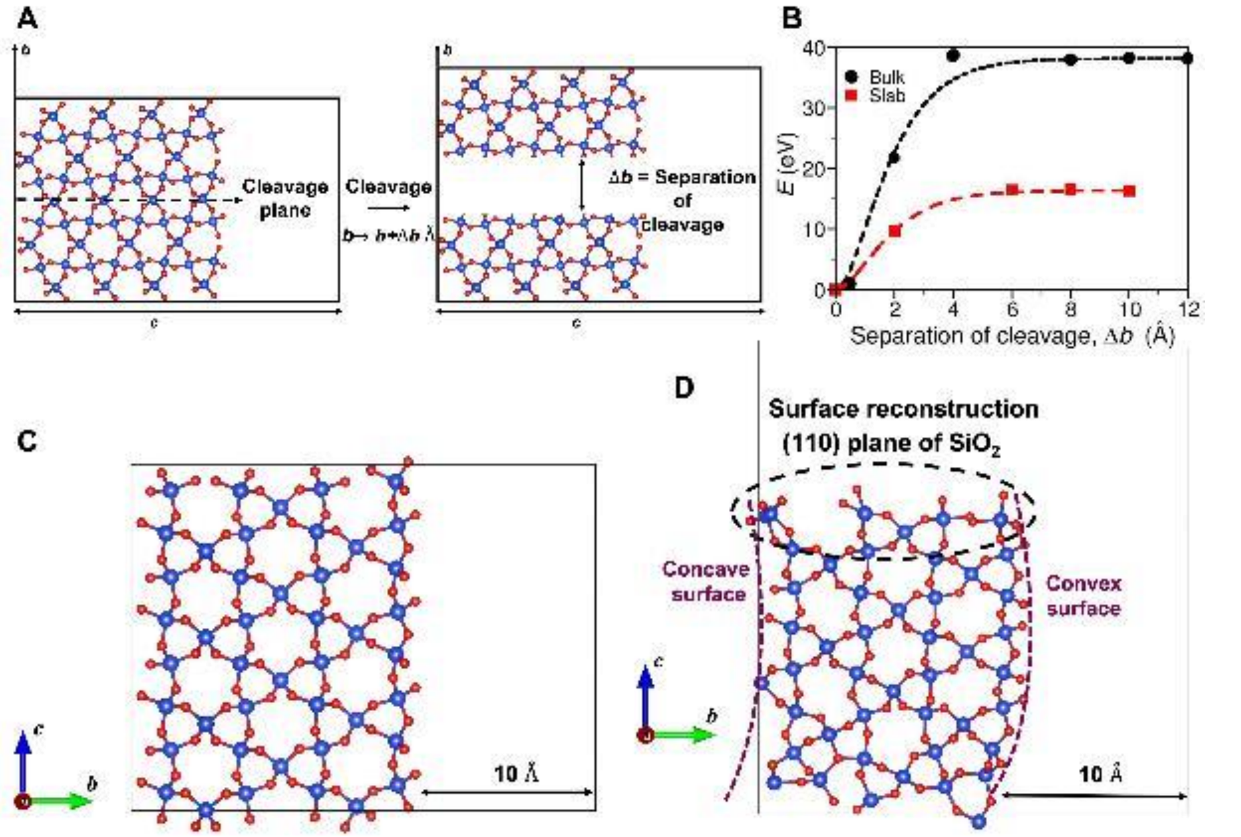
SiO_2 before electrospray

SiO_2 JCPDS data

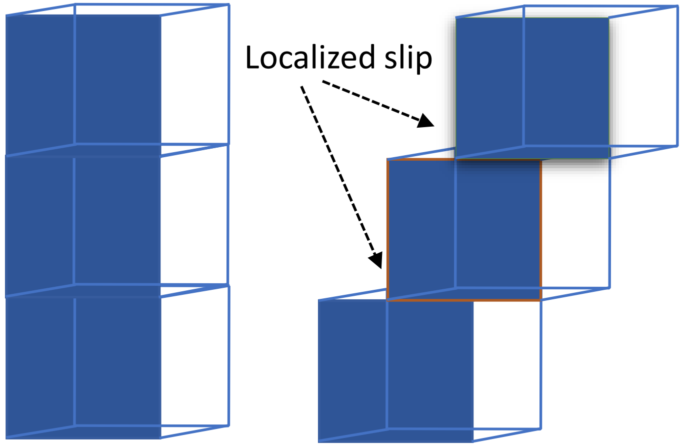
Mechanism: Cleavage

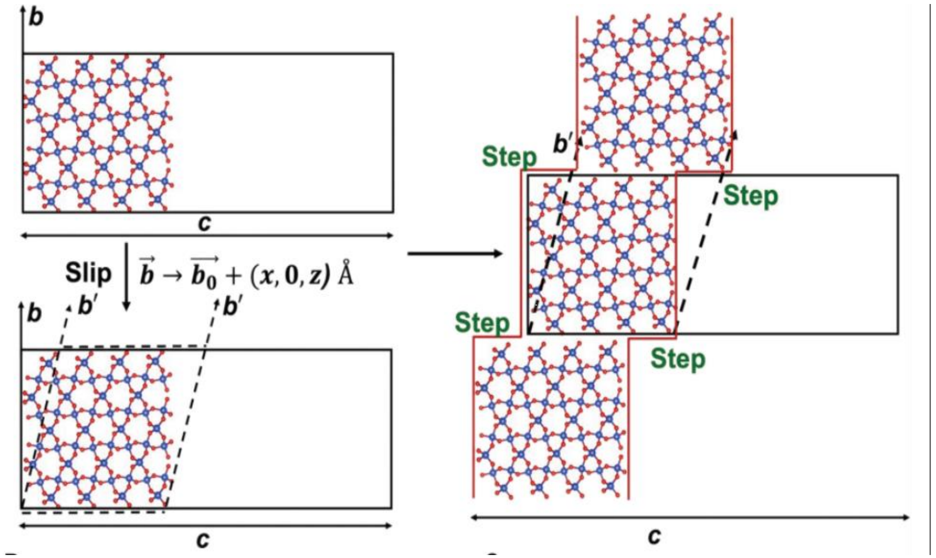


The process of cleavage and surface reconstruction visualized with first-principles simulations



Mechanism: Slip





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

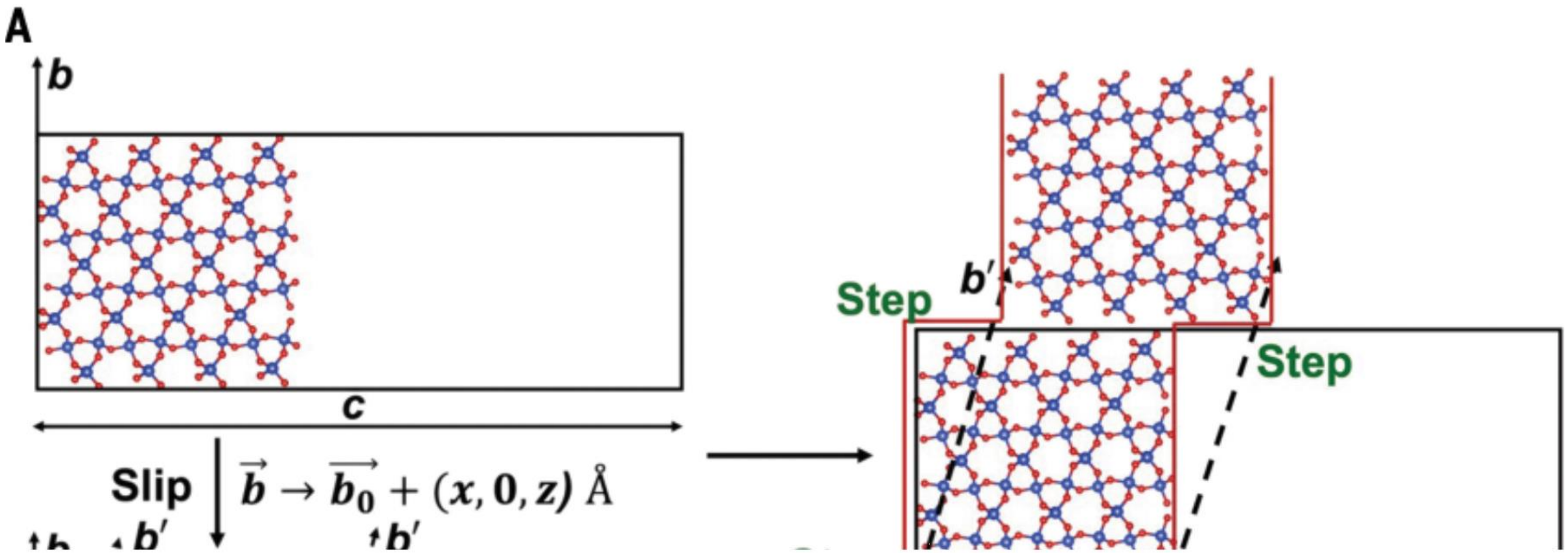
Stacking fault

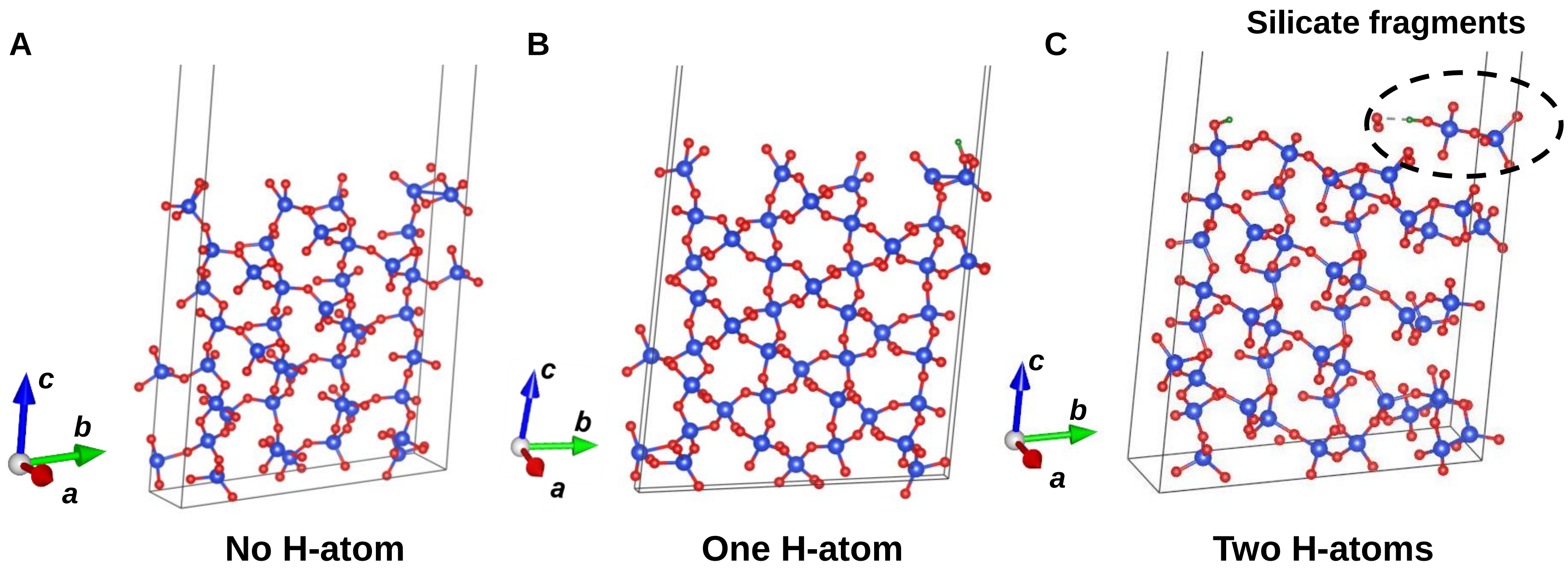
$\vec{b} \rightarrow \overrightarrow{b_0} + (x, 0, z)$

(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

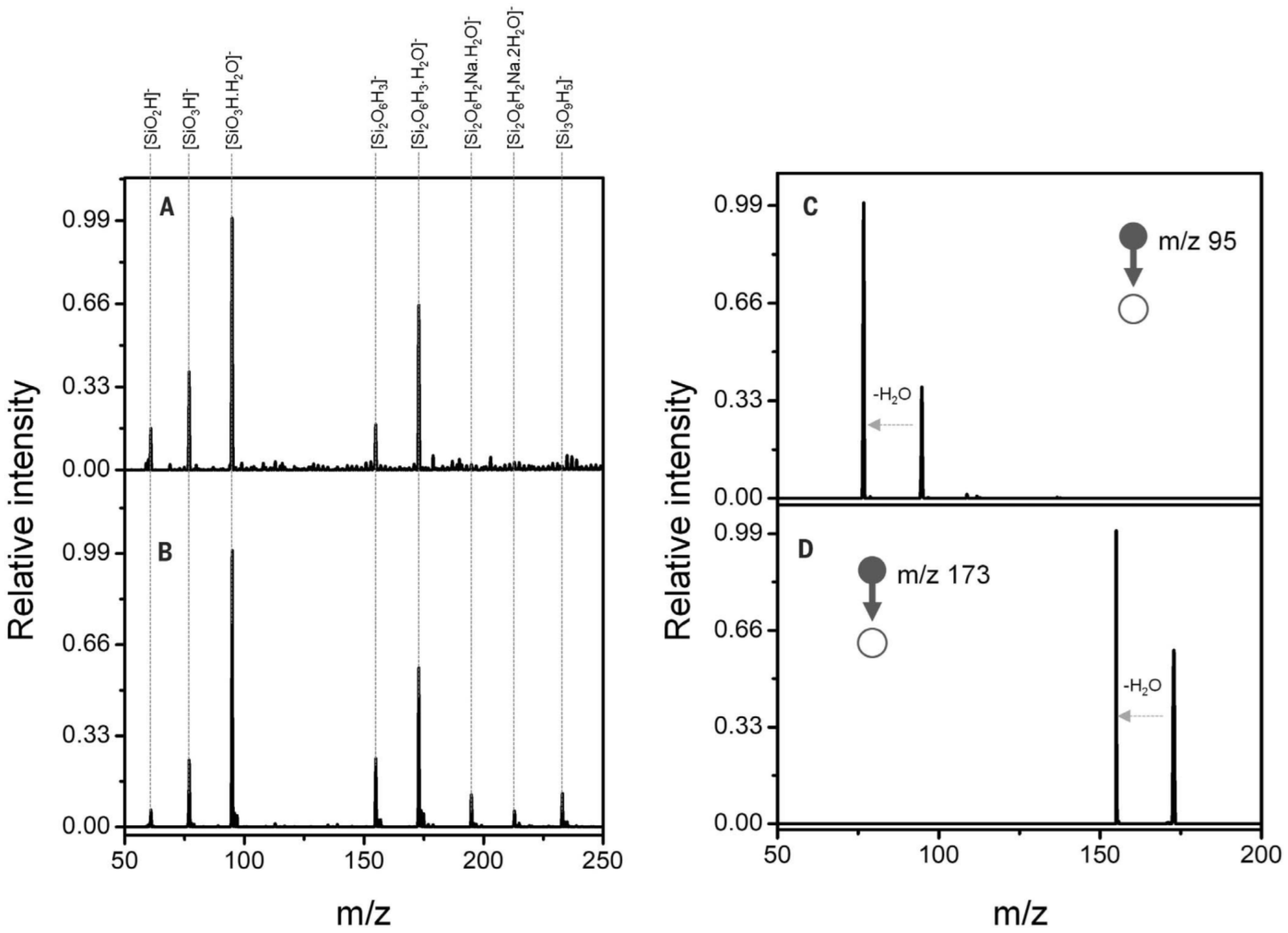
SFE (J/m^2)	Slab					
	x	z	w/o H-atom	1 H-atom	2 H-atoms	E
	0.0	0.0	0	0	0	0
	0.5	**0.5**	**-1.21**	**-0.93**	**-0.88**	**-1.20**
	0.5	0.0	1.20	1.18	0.90	1.12
	0.0	**0.5**	**-0.07**	**0.89**	**-0.83**	**-0.09**



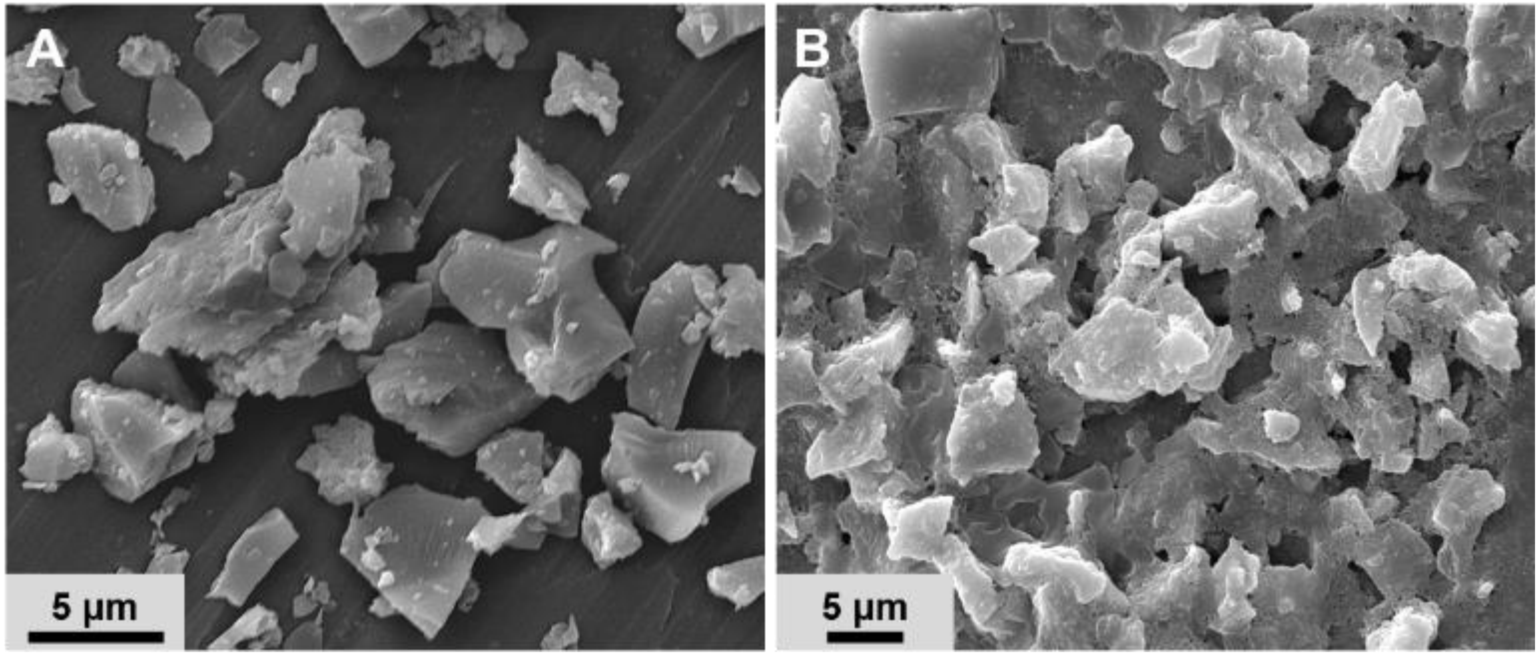


A
B
C
Silicate fragments
c
b
a
c
b
a
c
b
a
No H-atom
One H-atom
Two H-atoms

Mass Spectrometry of the Fragments

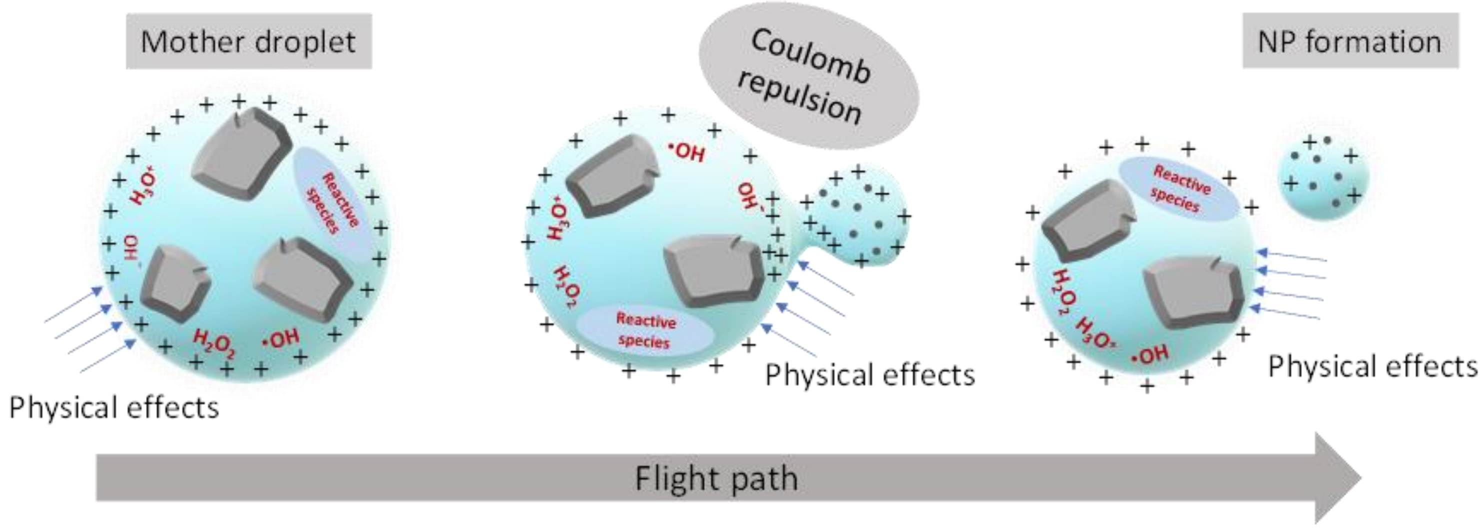


Effect of charged microdroplets on quartz



Increased surface roughness after the spray

Mechanism of nanoparticle formation



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

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

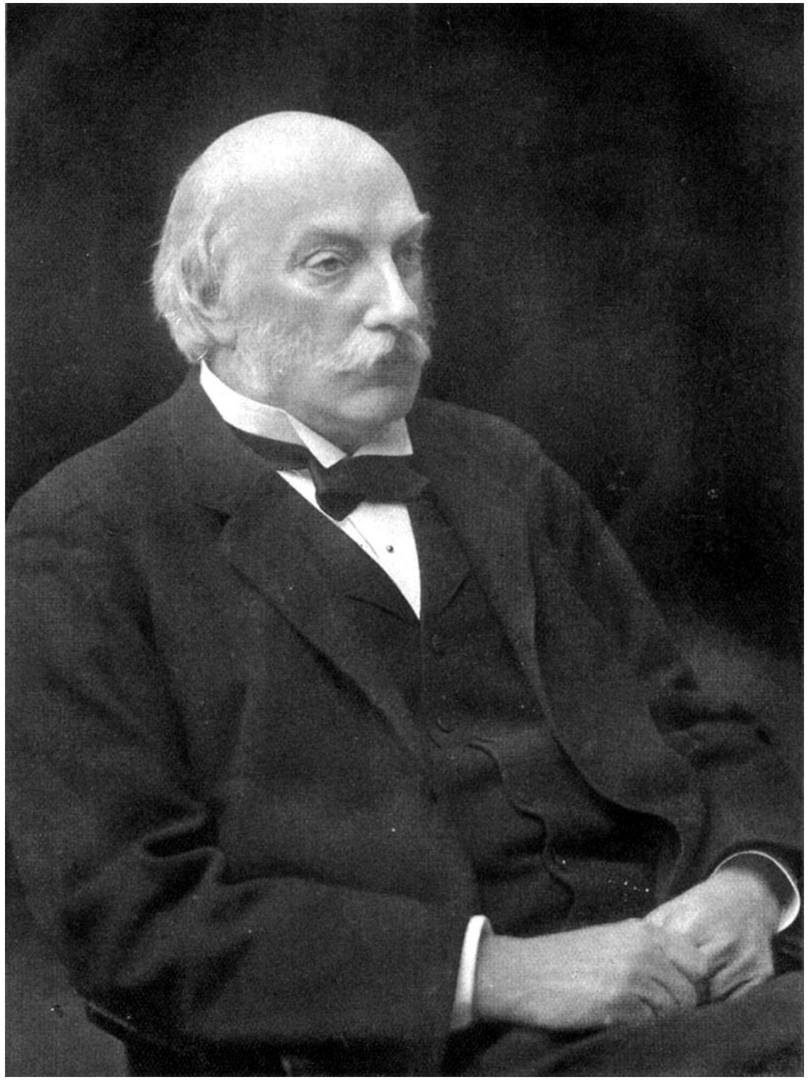
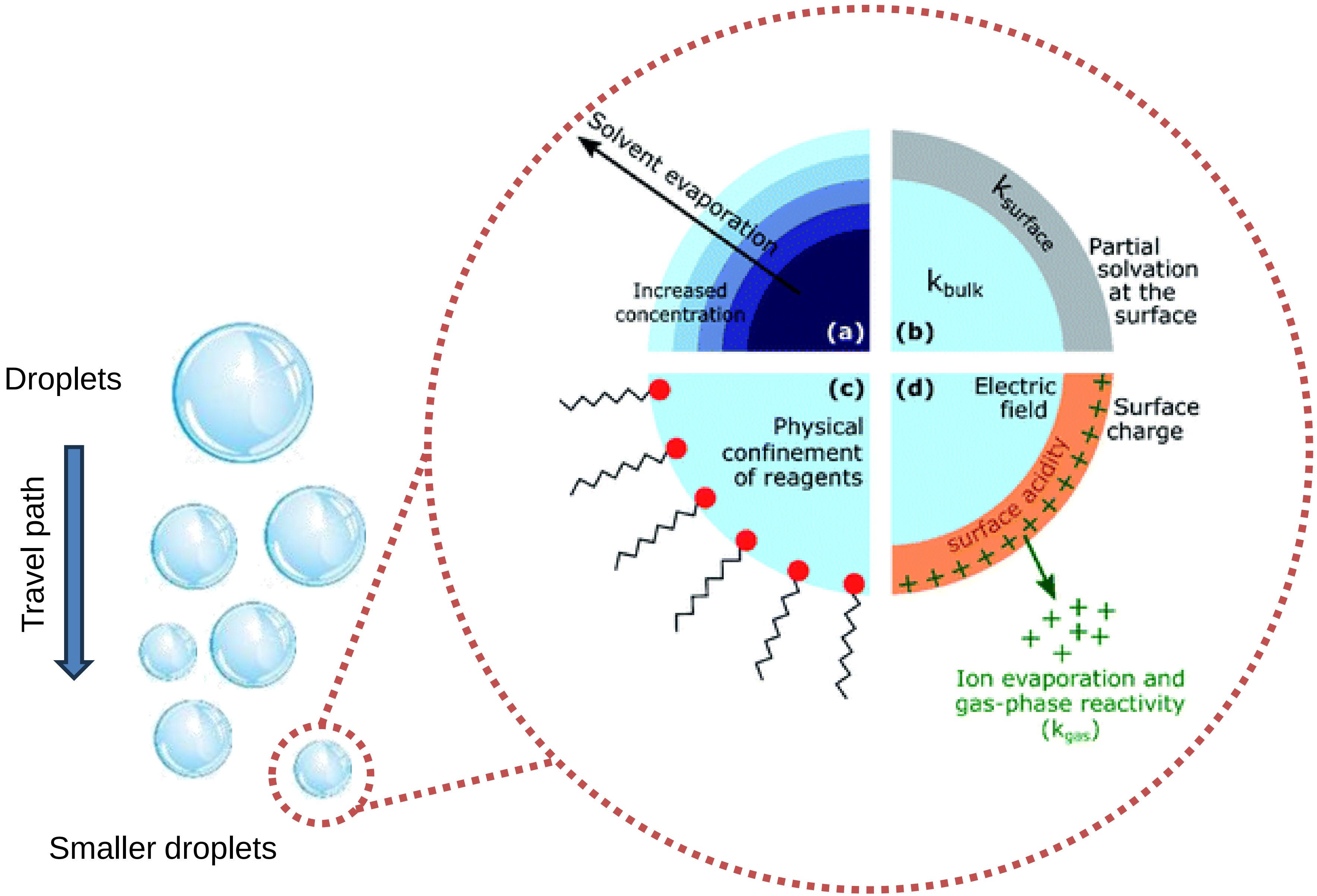


Image from Wikipedia

Understanding Microdroplets



Grazia Rovelli, et. al. *Chem. Sci.*, 2020, 11, 13026–13043.

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 that 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.

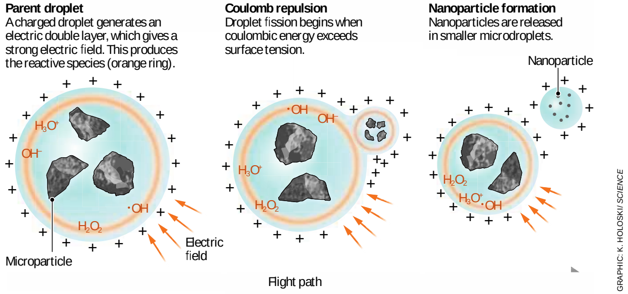
The unusual chemical nature of the air-water interface results in much remarkable chemistry. For example, amino acids in water undergo dehydration to form peptides in this environment (*6*), whereas bulk water simply solvates amino acids. The superacidic interface activates amino acids and removes water 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 ($H_2O^{•+}/H_2O^{•-}$) coexists with oxidative species such as hydrogen peroxide (H_2O_2) and OH•. These redox species enable a variety of spontaneous chemical transformations, including carbon-oxygen 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 microdoplets. Key reactive species are the result of the effects of a high electric field at the surface of the water droplets.

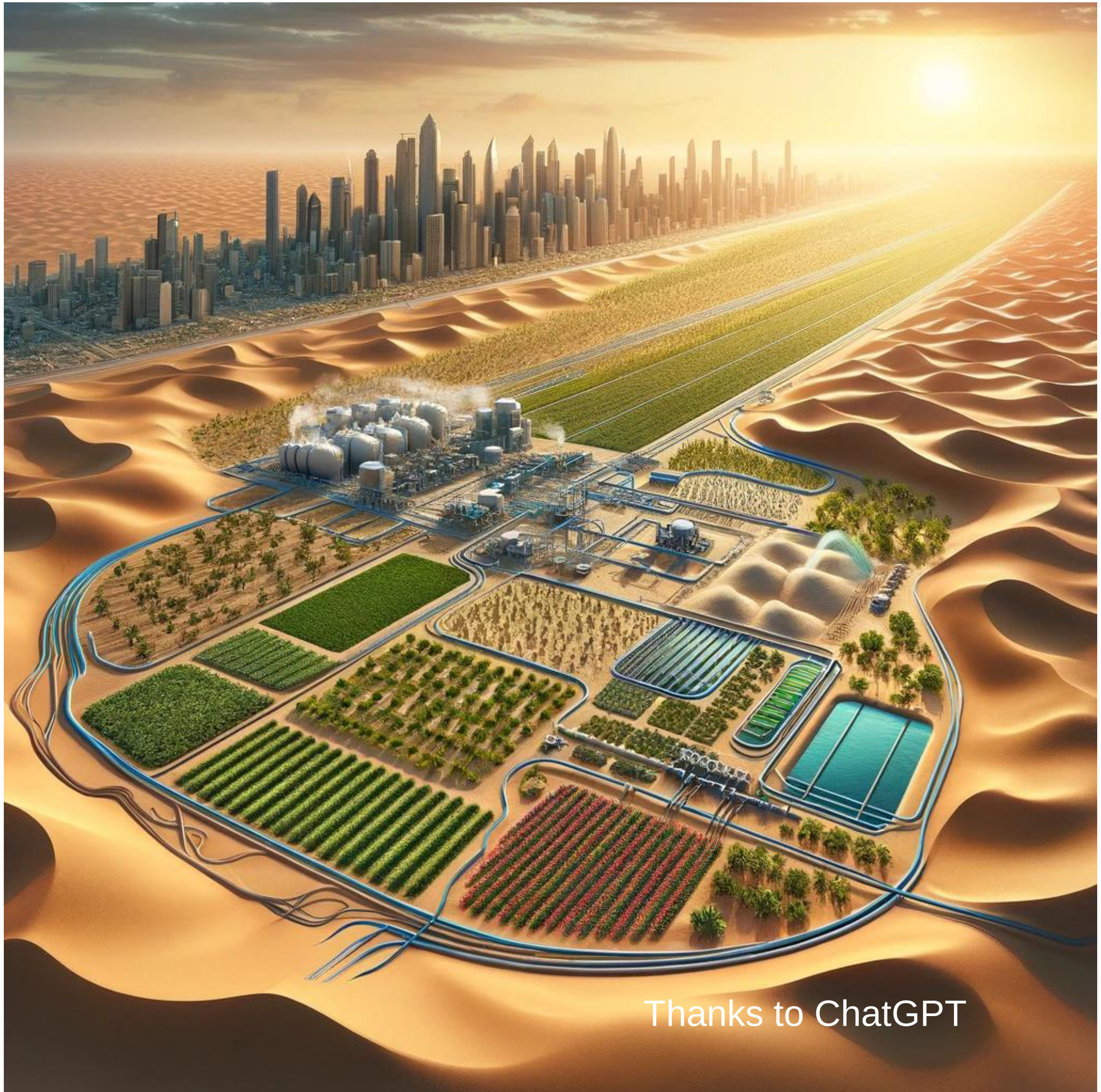


Department of Chemistry, Purdue University, West Lafayette, IN, USA. Email: cooks@purdue.edu

Thanks to ChatGPT

Vision

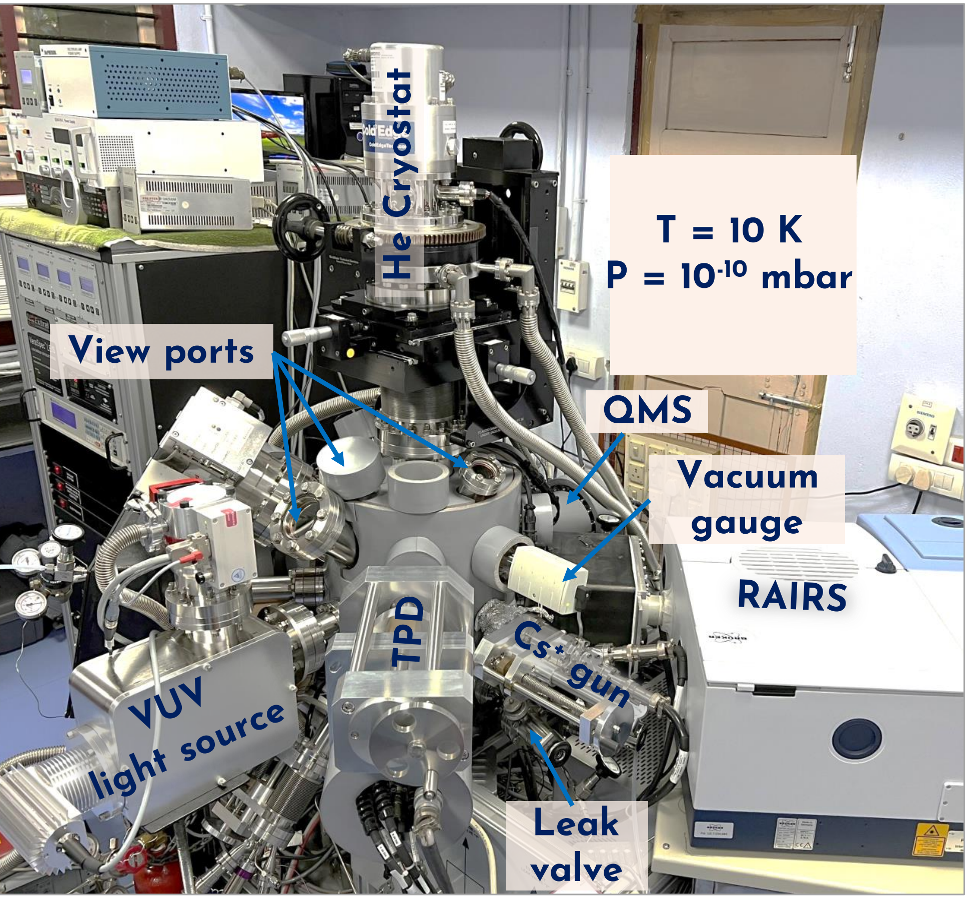
Make soil using processed wastewater and make deserts bloom.

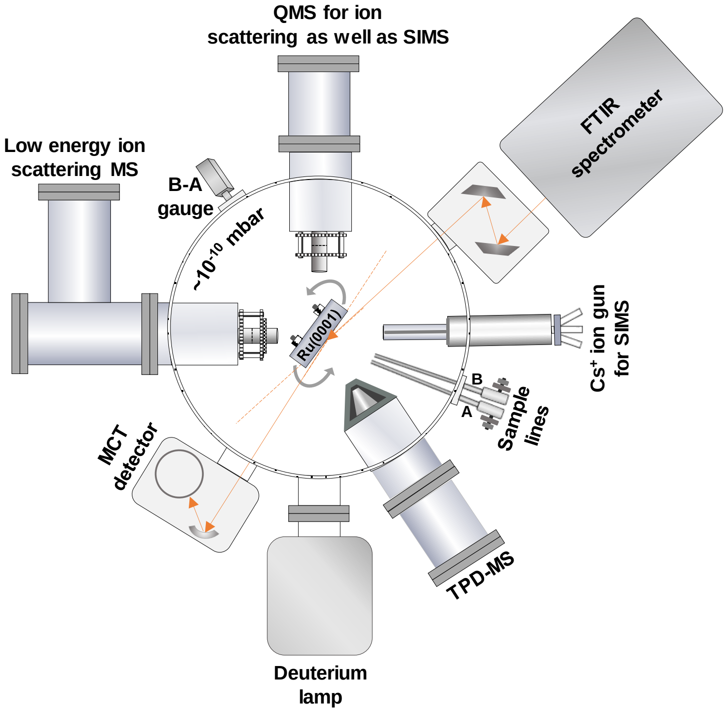


Can Clathrate Hydrates Exist in Space?

Exploring astrobiology

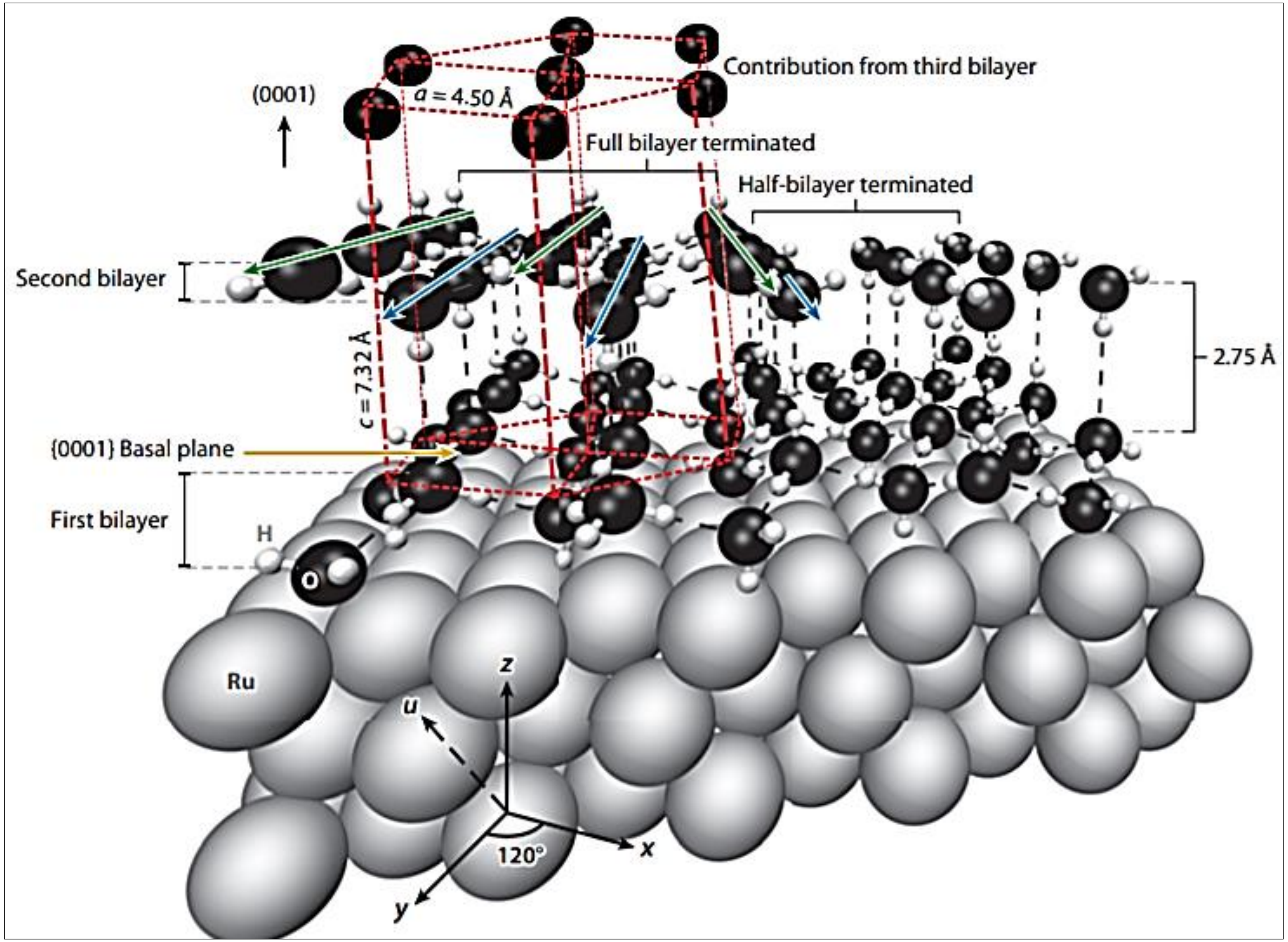
Instrumentation





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



Bag, S. *et al.*, *Annu. Rev. Anal. Chem.* **2013**, *6*, 97–118

ACCOUNTS
of chemical research

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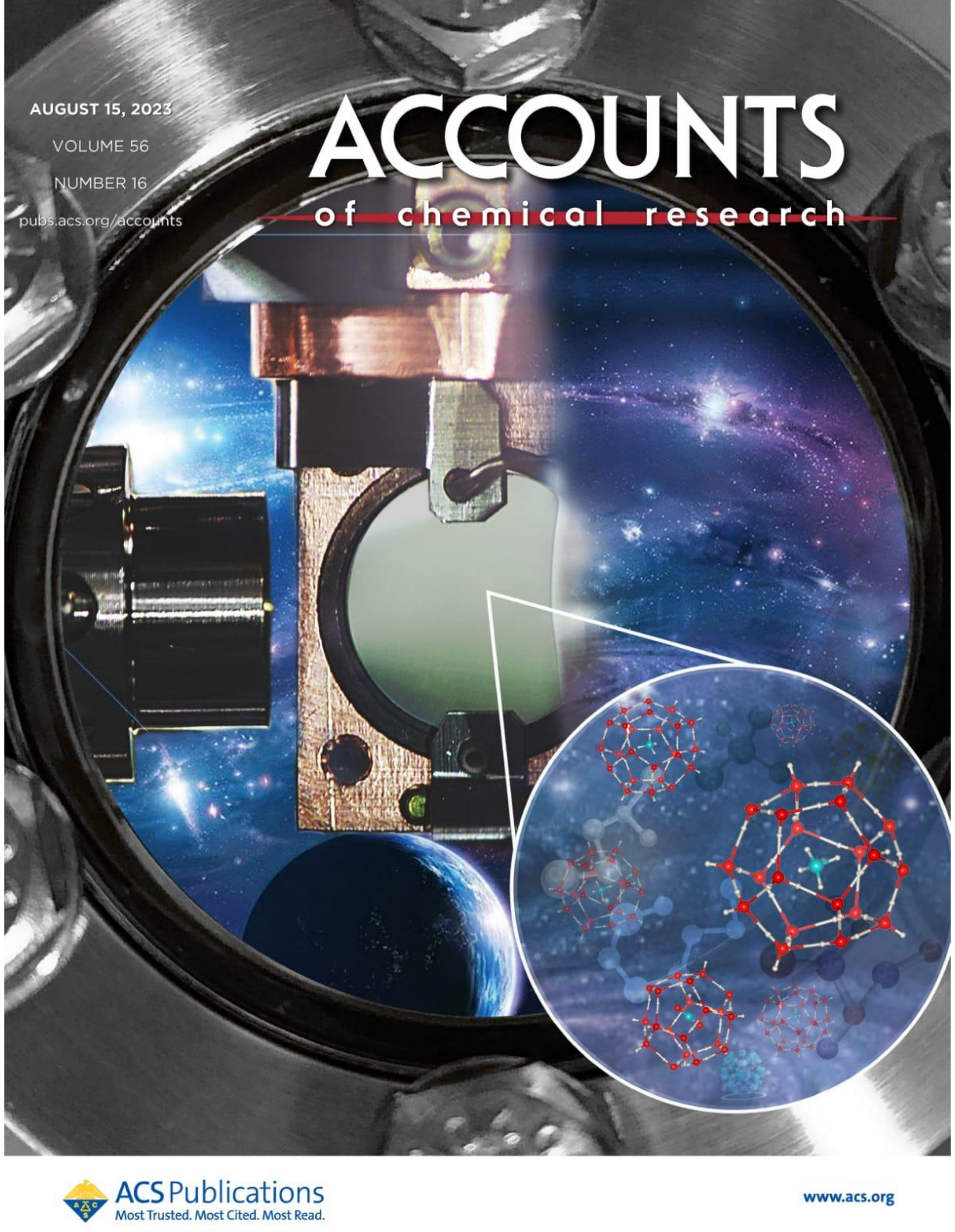
Article

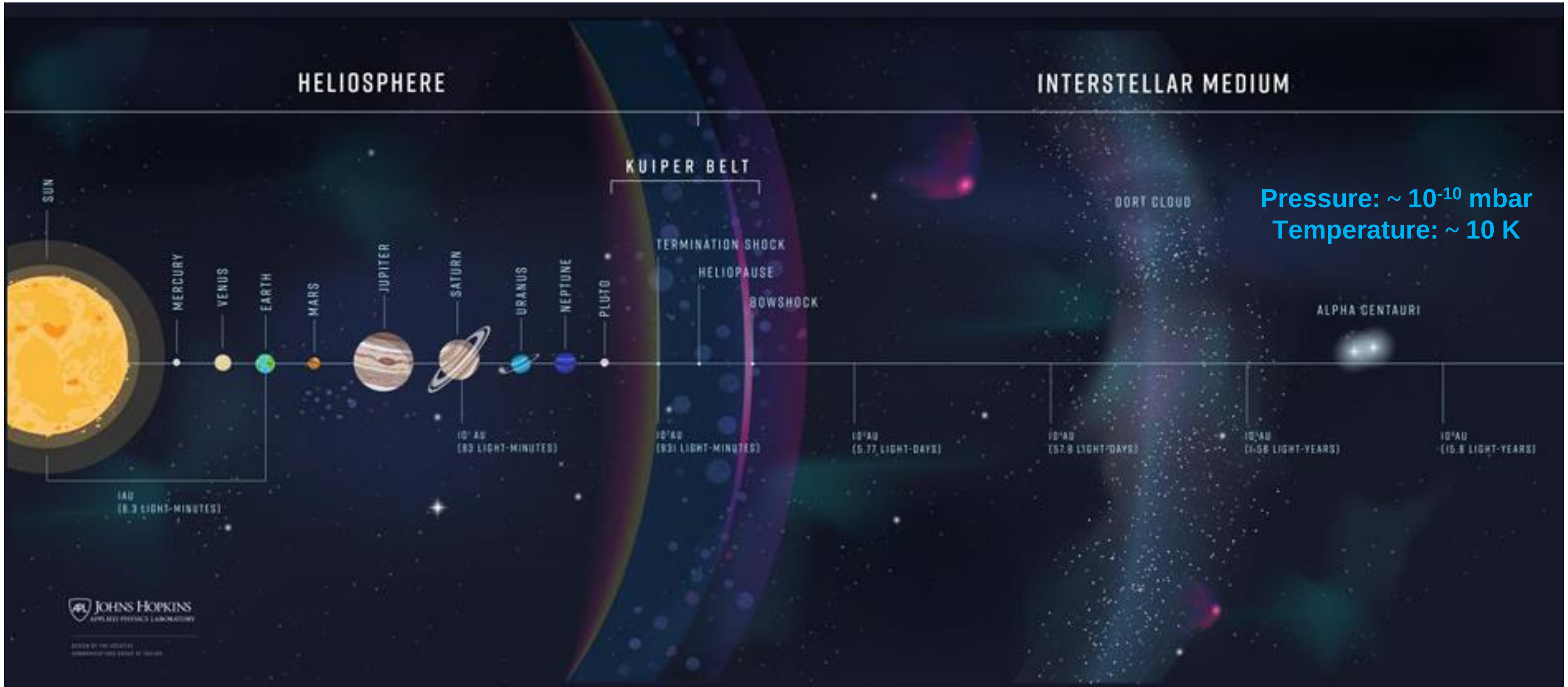
Formation and Transformation of Clathrate Hydrates under Interstellar Conditions

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

Cite This: https://doi.org/10.1021/acs.accounts.3c00317
Read Online



Interstellar medium

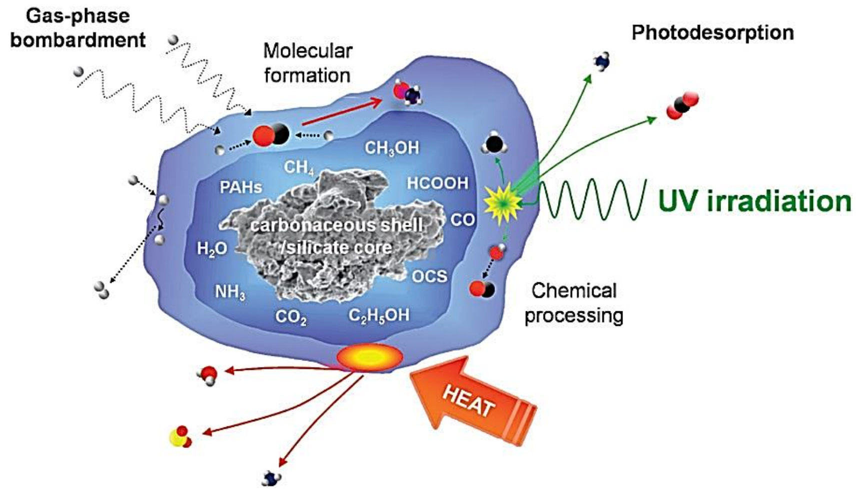


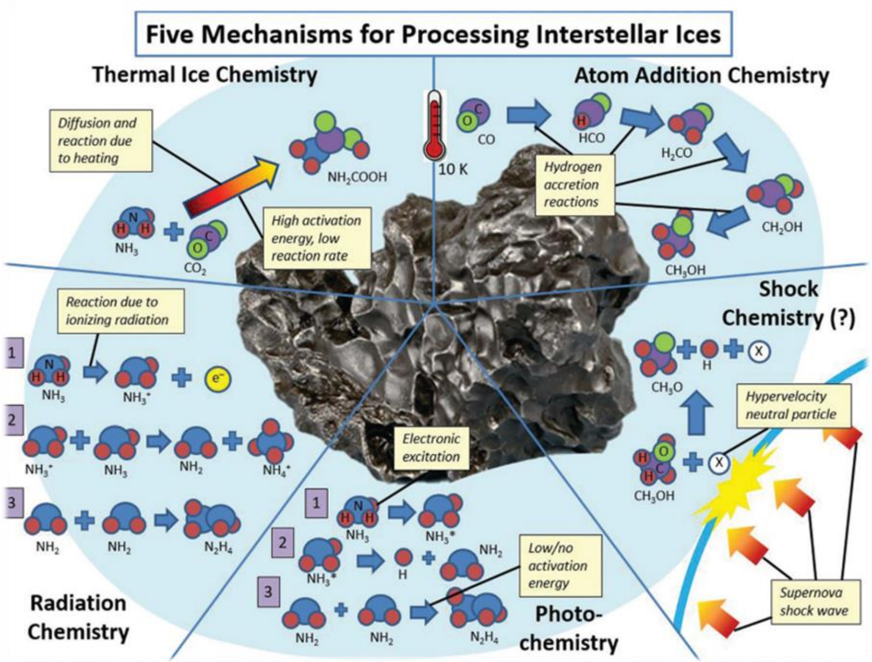
Pressure: ~ 10^{-10} mbar
Temperature: ~ 10 K

Diffuse clouds: T ~ 100 K, n ~ 100 molecules per cm^3
Dense clouds: T ~ 10-100 K, n ~ 10^4-10^8 molecules per cm^3
On Earth sea level: T ~ 300 K, n ~ 3×10^{19} molecules per cm^3

https://spaceref.com/science

Interstellar ices





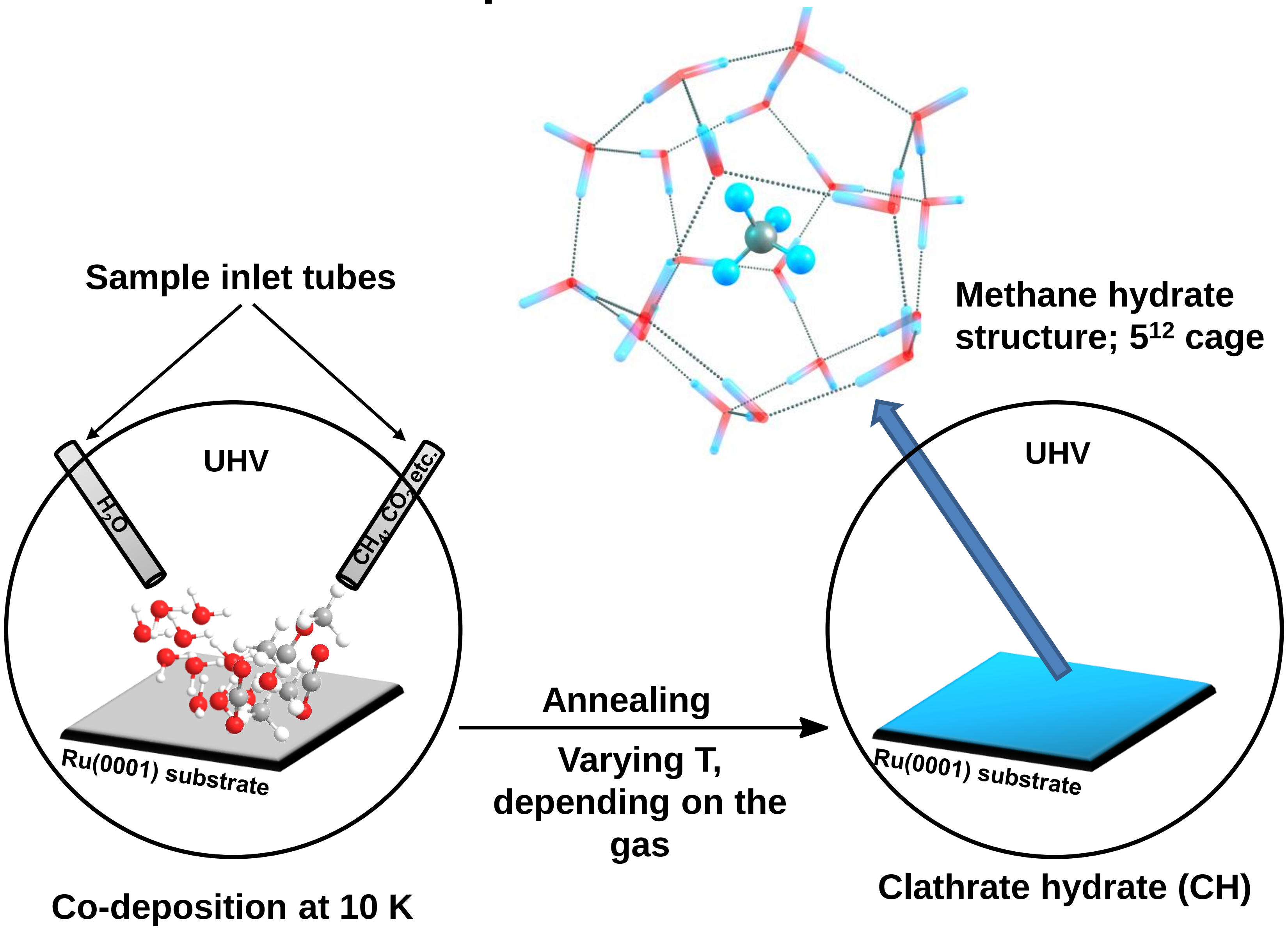
Silicates and carbonaceous material – 0.01-0.5 µm

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

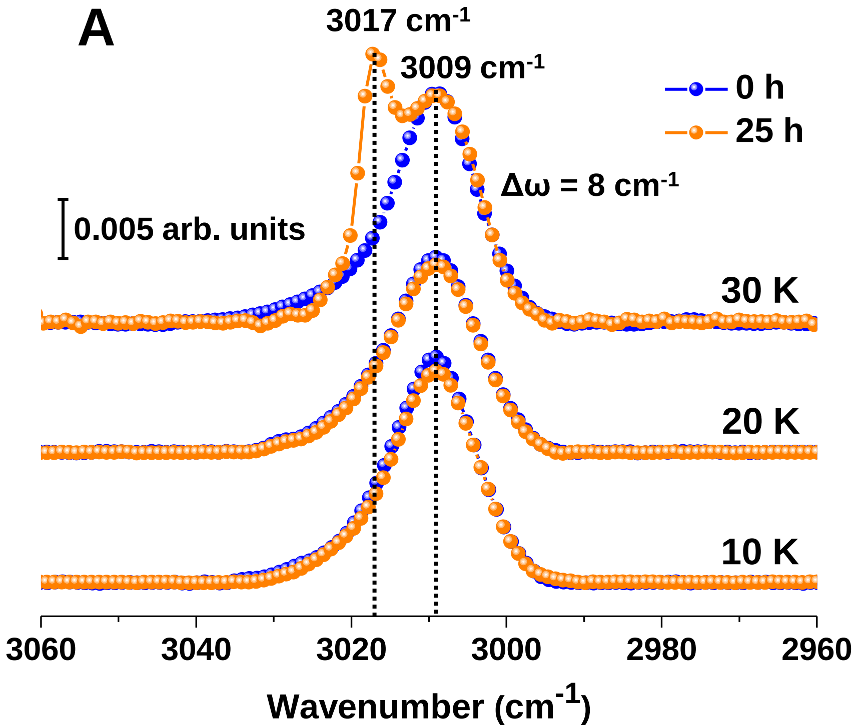
Clathrate hydrates in interstellar environment

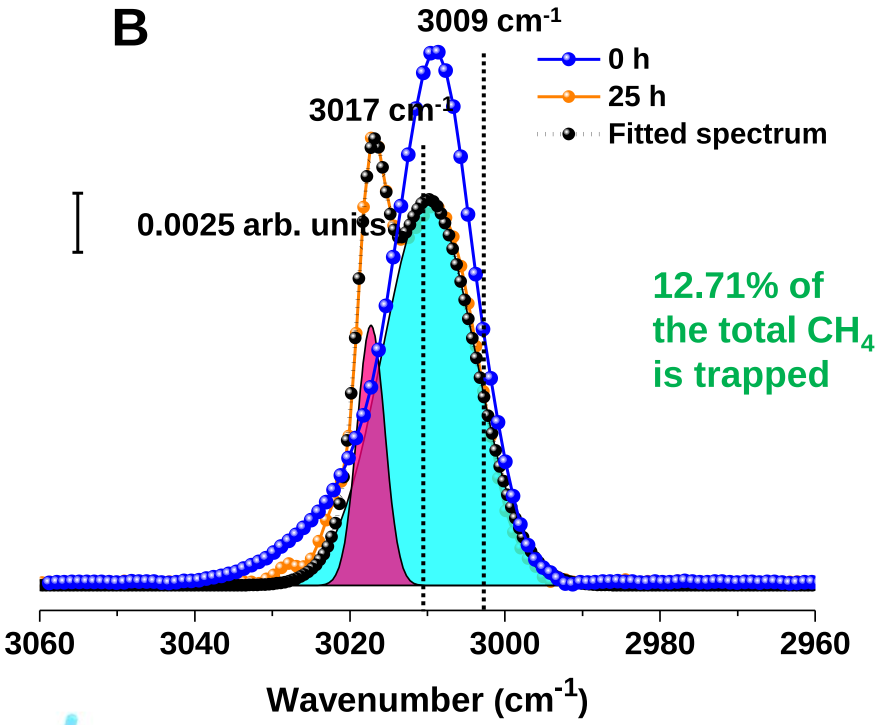
Ghosh, J. *et al.*, *Proc. Natl. Acad. Sci. U.S.A.*, **2019**, *116*, 1526-1531

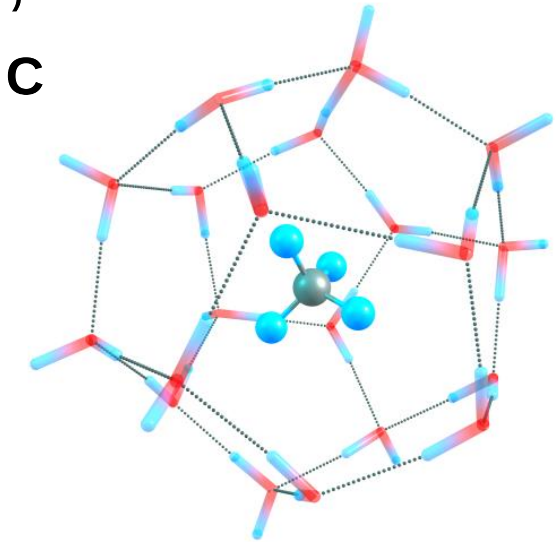
Experimental method



Clathrate hydrates in interstellar environment



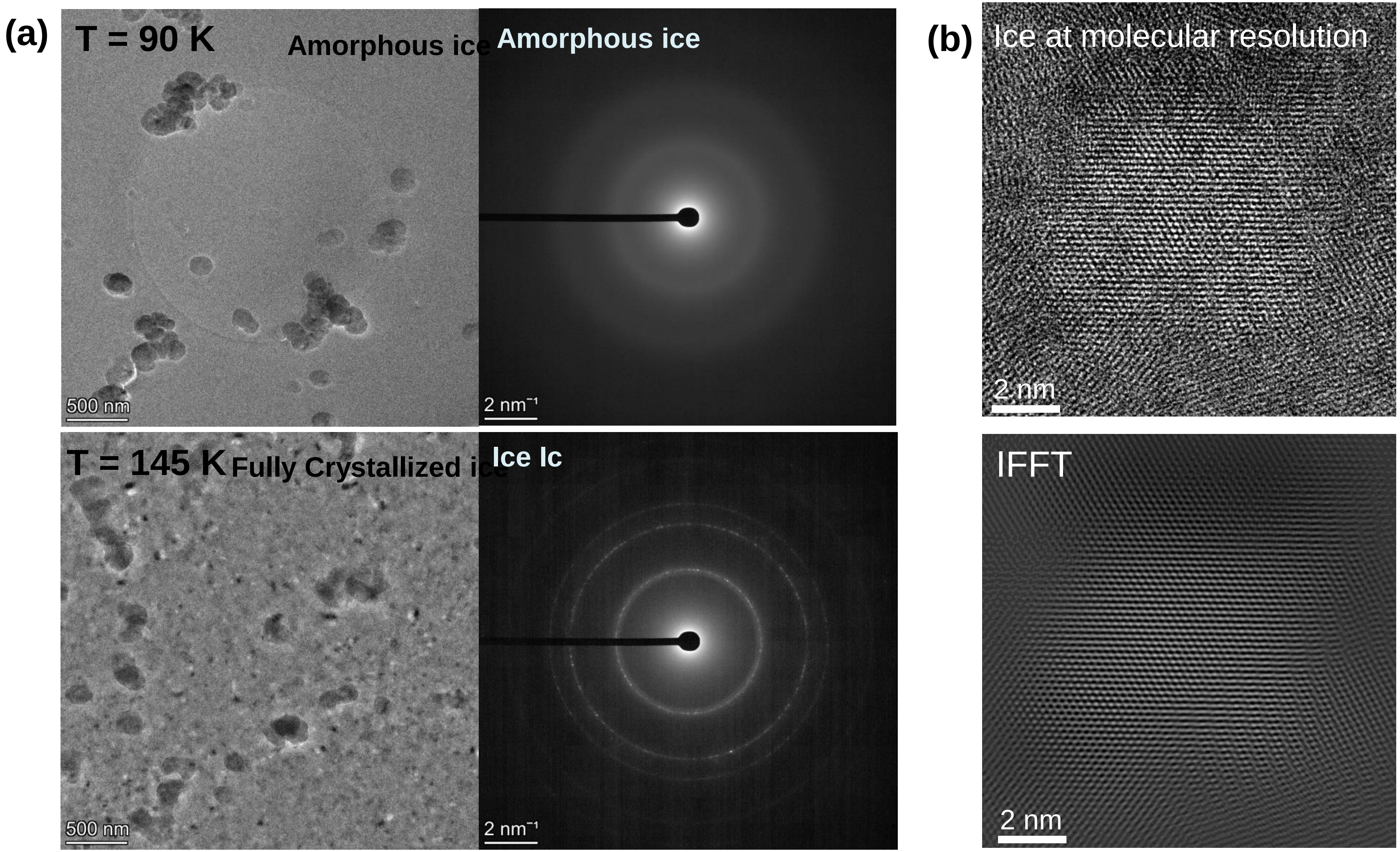




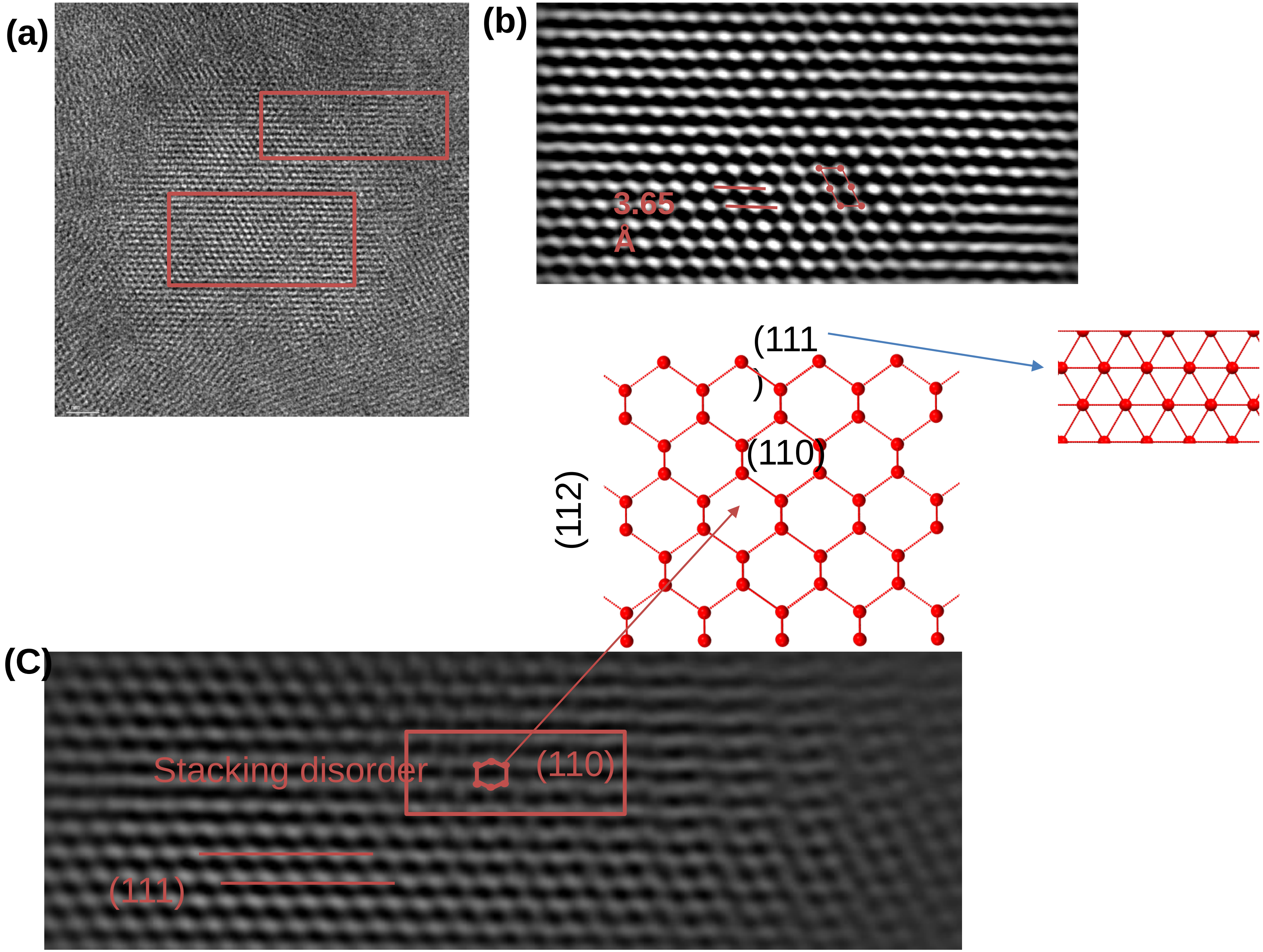
5^{12} cage of CH_4 hydrate

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

Observing growth of crystalline ice from amorphous ice

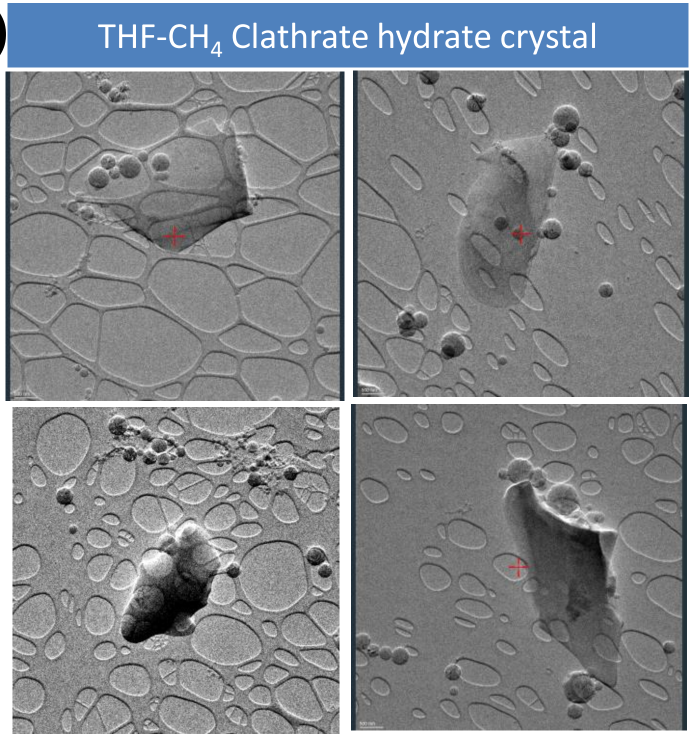


Imaging cubic ice at molecular resolution

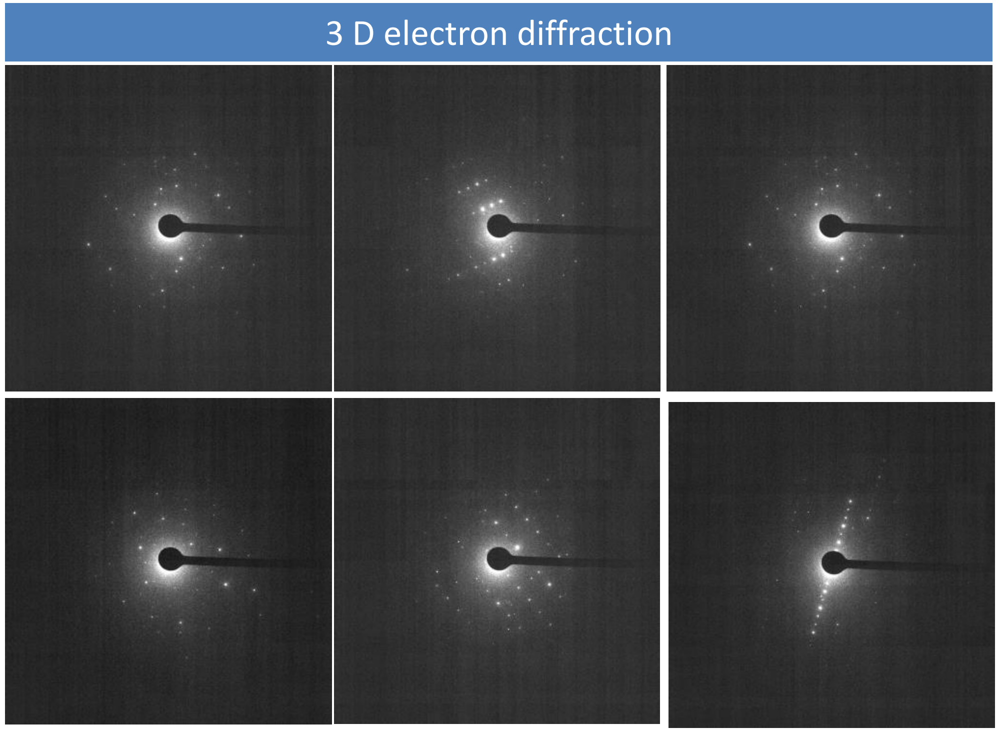


Electron diffraction of nanometer-scale crystals of clathrate hydrate

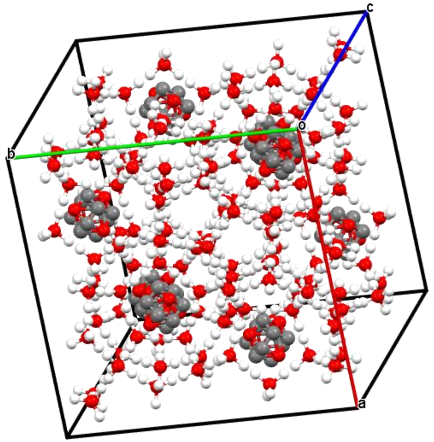
(a)

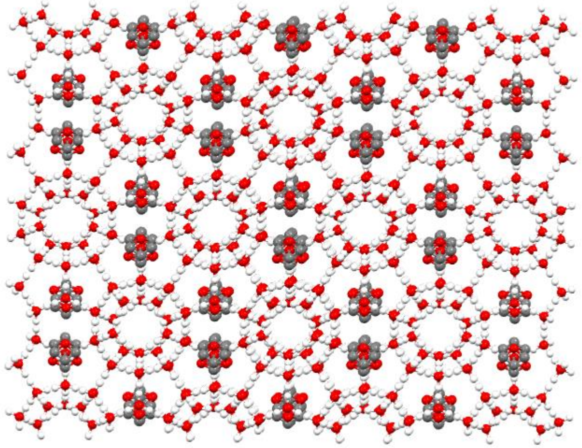


(b)



(c)



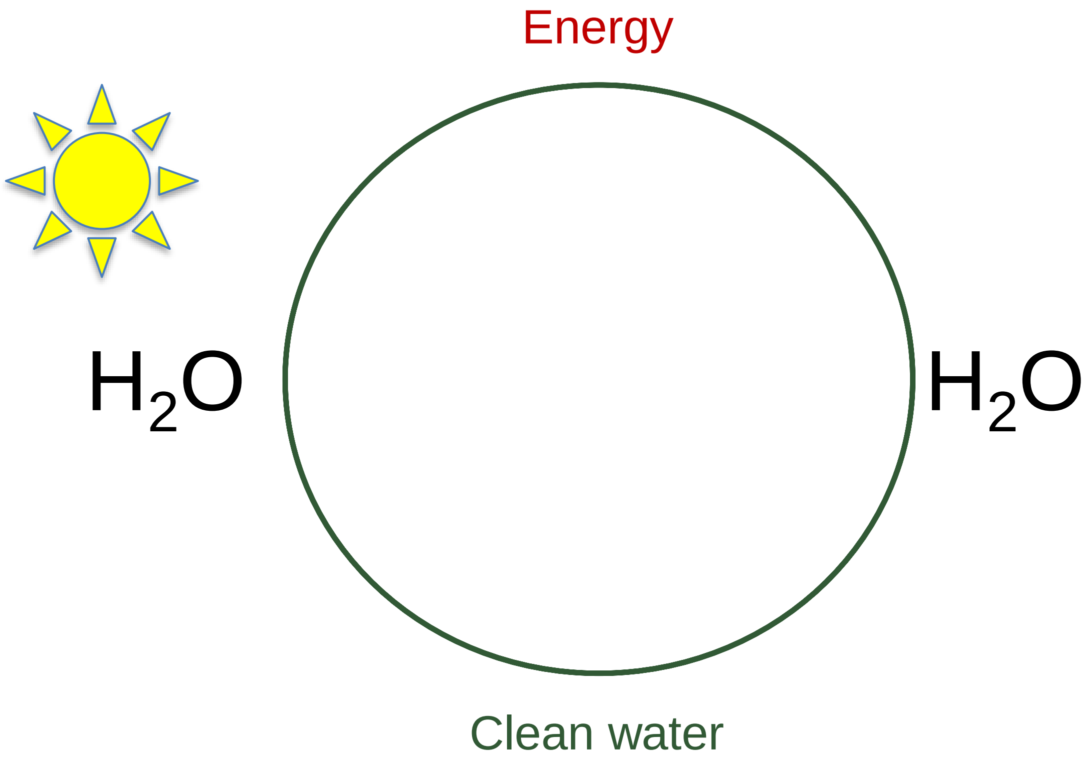


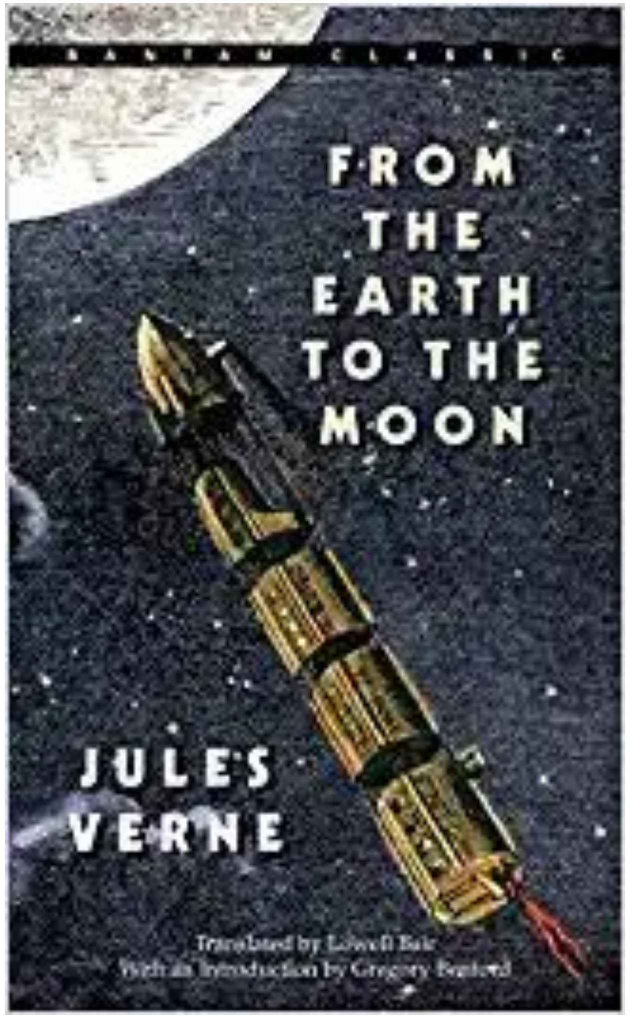
Crystal structure


thermoscientific
ThermoFisher
SCIENTIFIC


International Centre for Clean Water

Our dreams become reality with materials





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

An ocean of opportunities

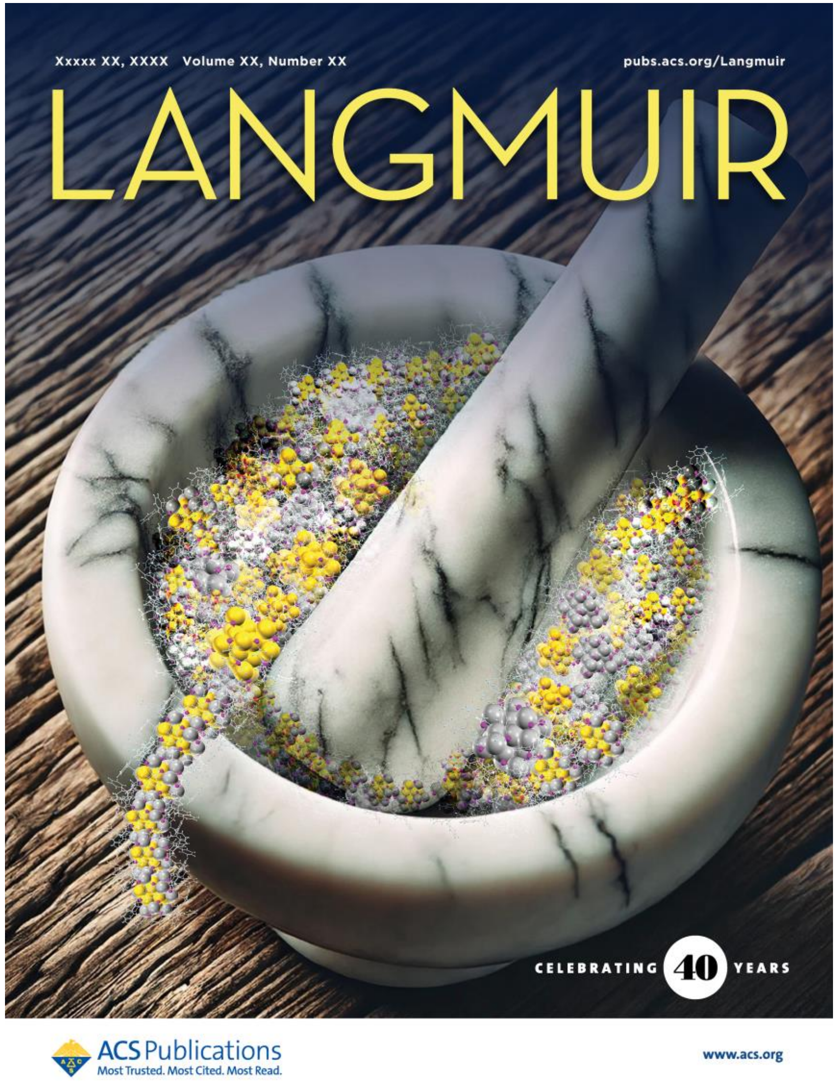
Water presents a unique opportunity to find a purpose in life.

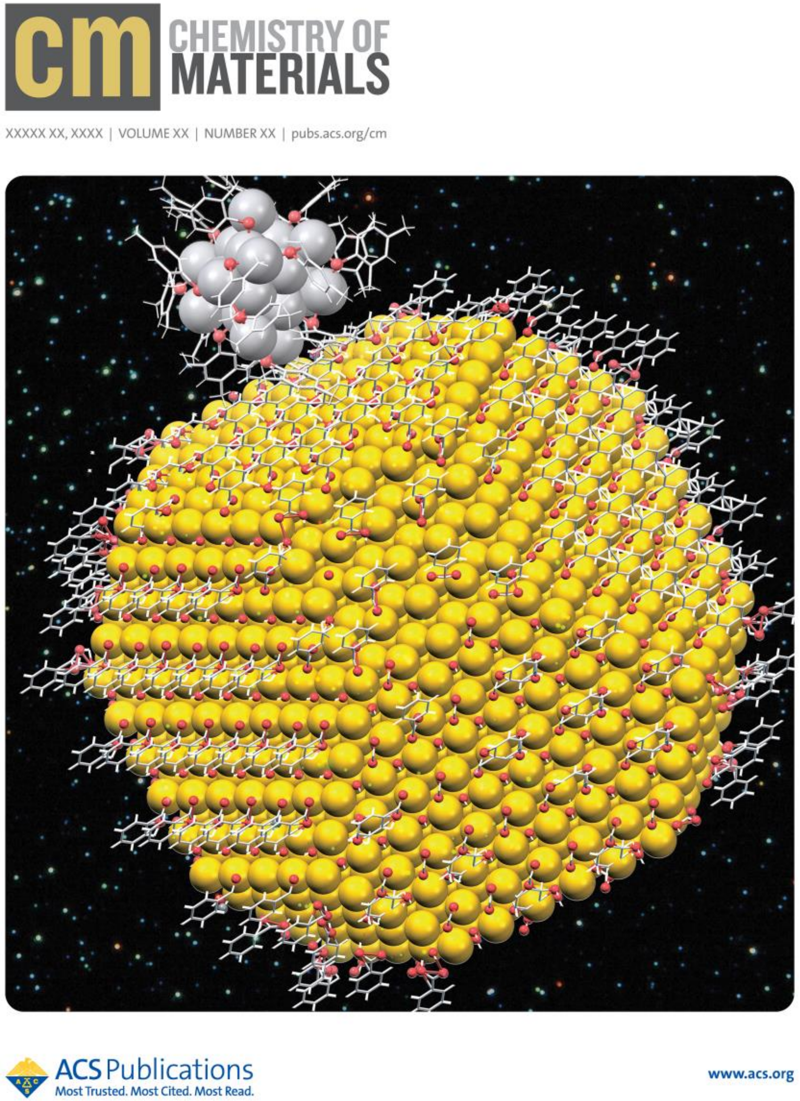
Earthrise, taken on December 24, 1968, by Apollo astronaut William Anders. From Wikipedia

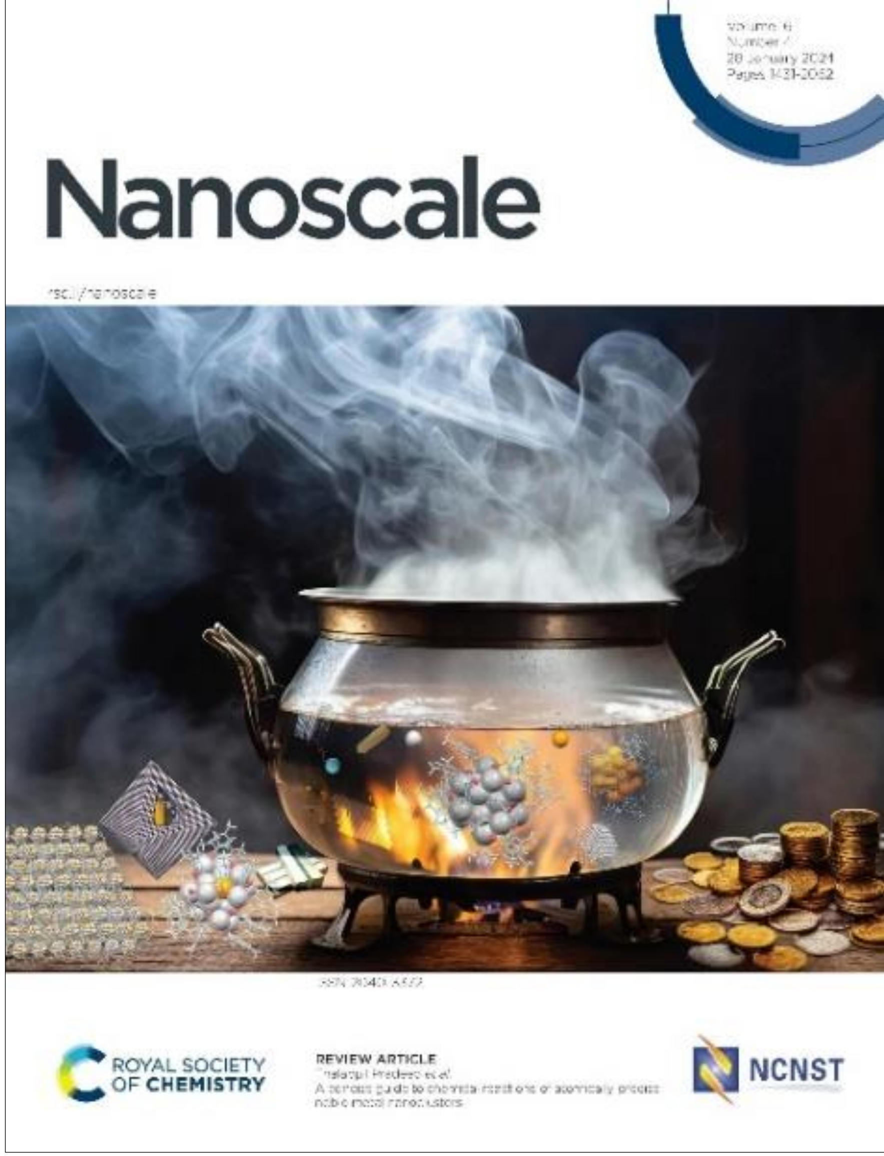
Conclusions

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





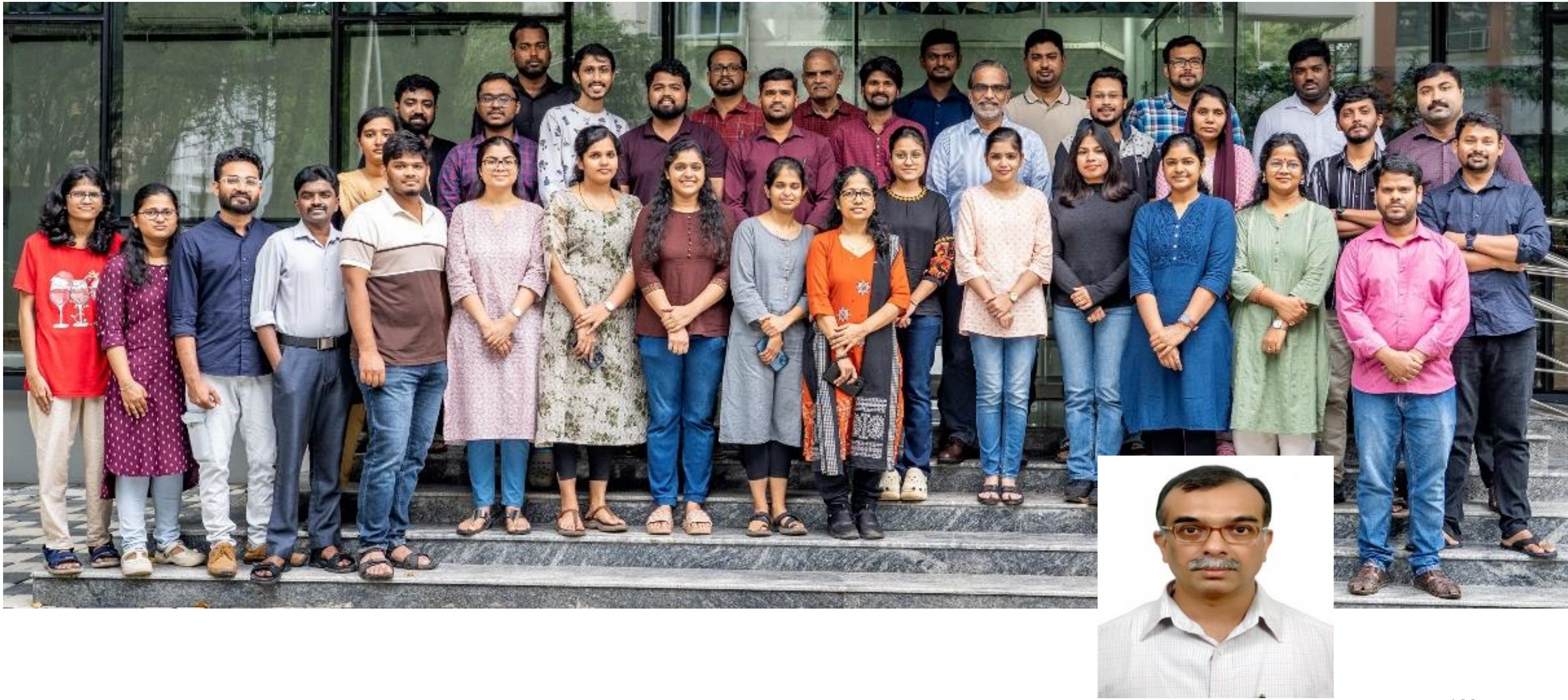


Department of Science and Technology

Institute of Eminence

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

Start-ups and partners:

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MS Theses: Ananthu Mahedranath, Ramesh Kumar Soni

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

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Manswita Mandal for help with the slides