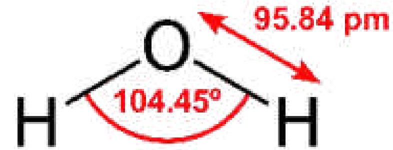
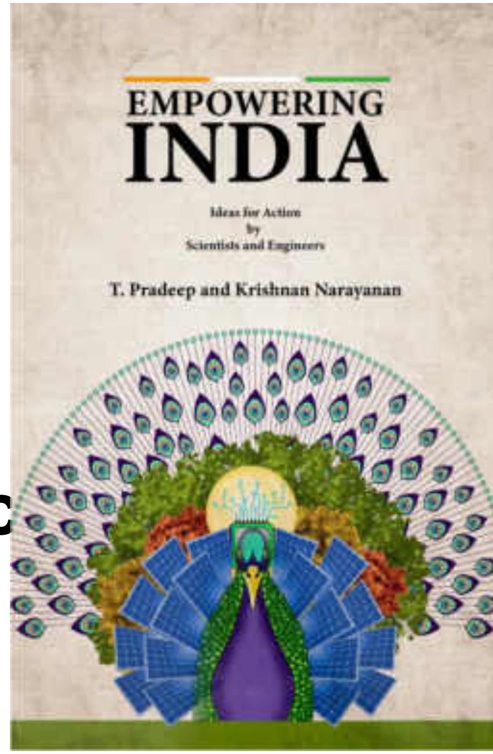
Since 1959





Affordable c ing advanced materials

radeep
, IIT Madras
pradeep@iitm.ac.in
https://pradeepresearch.org

Amitava Patra

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.

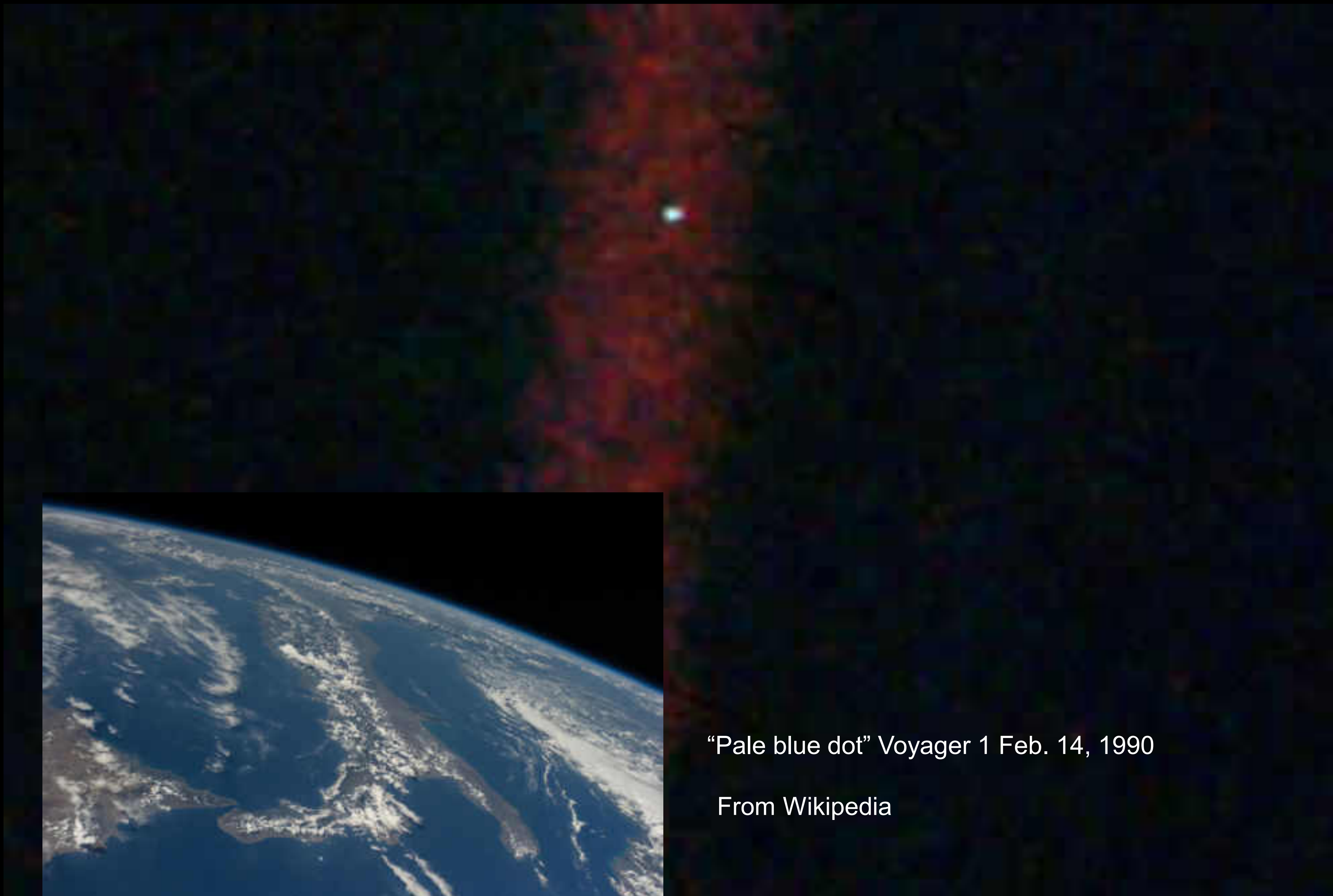
Associate Editor

ACS Sustainable Chemistry & Engineering

Professor-in-charge

International Centre for Clean Water

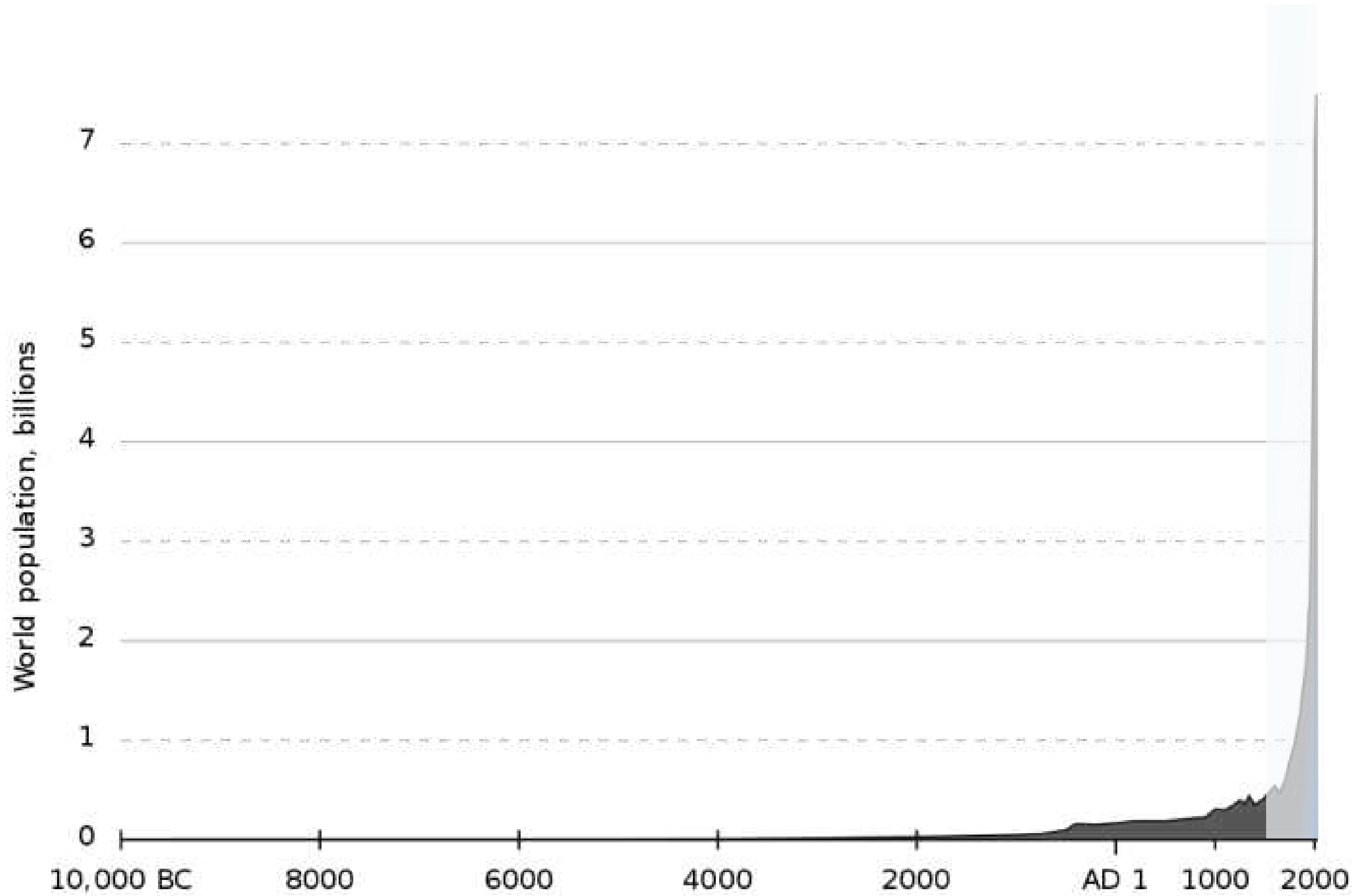
Institute of Nano Science and Technology, March 15, 2023



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

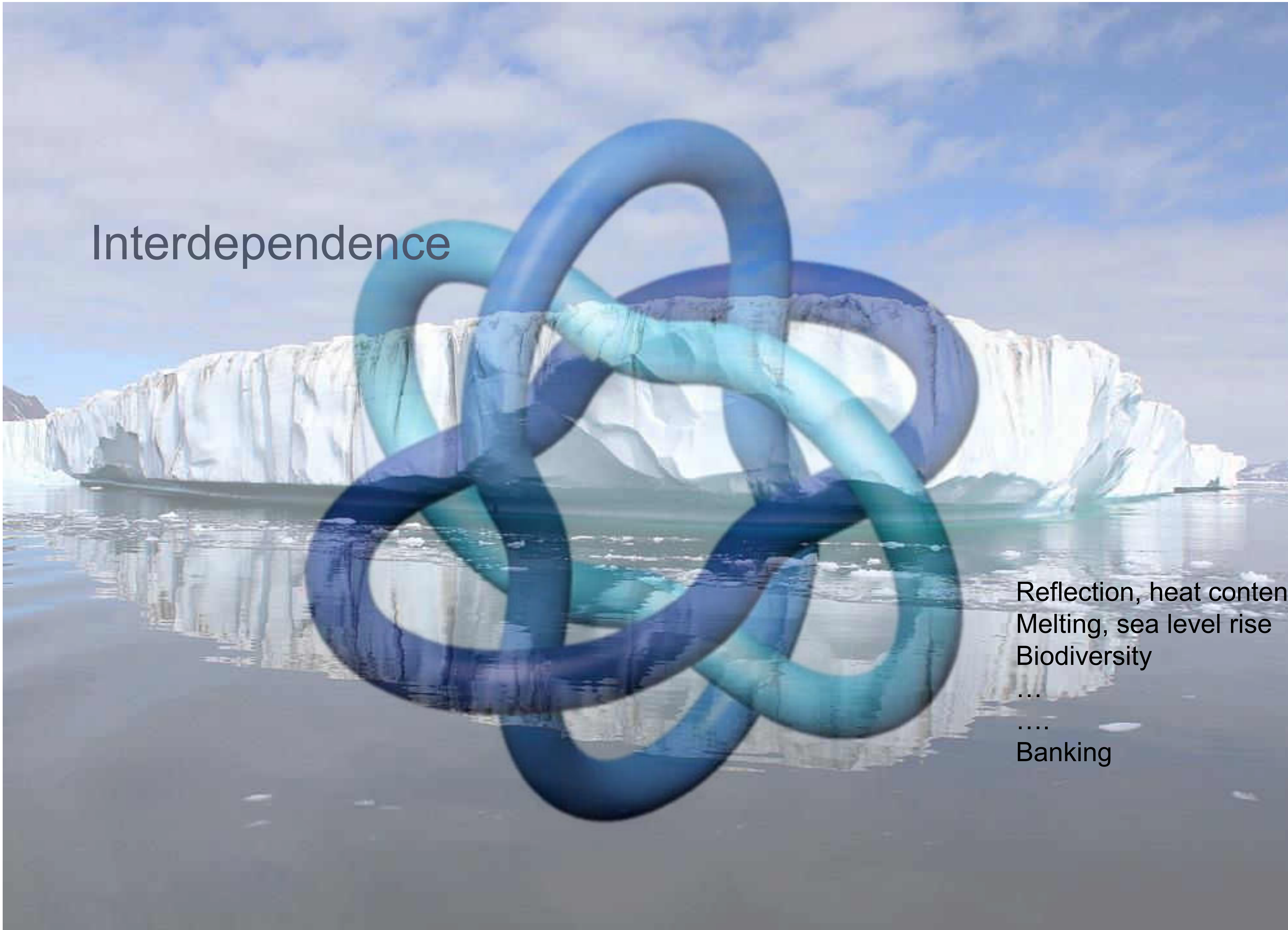
From Wikipedia

World population

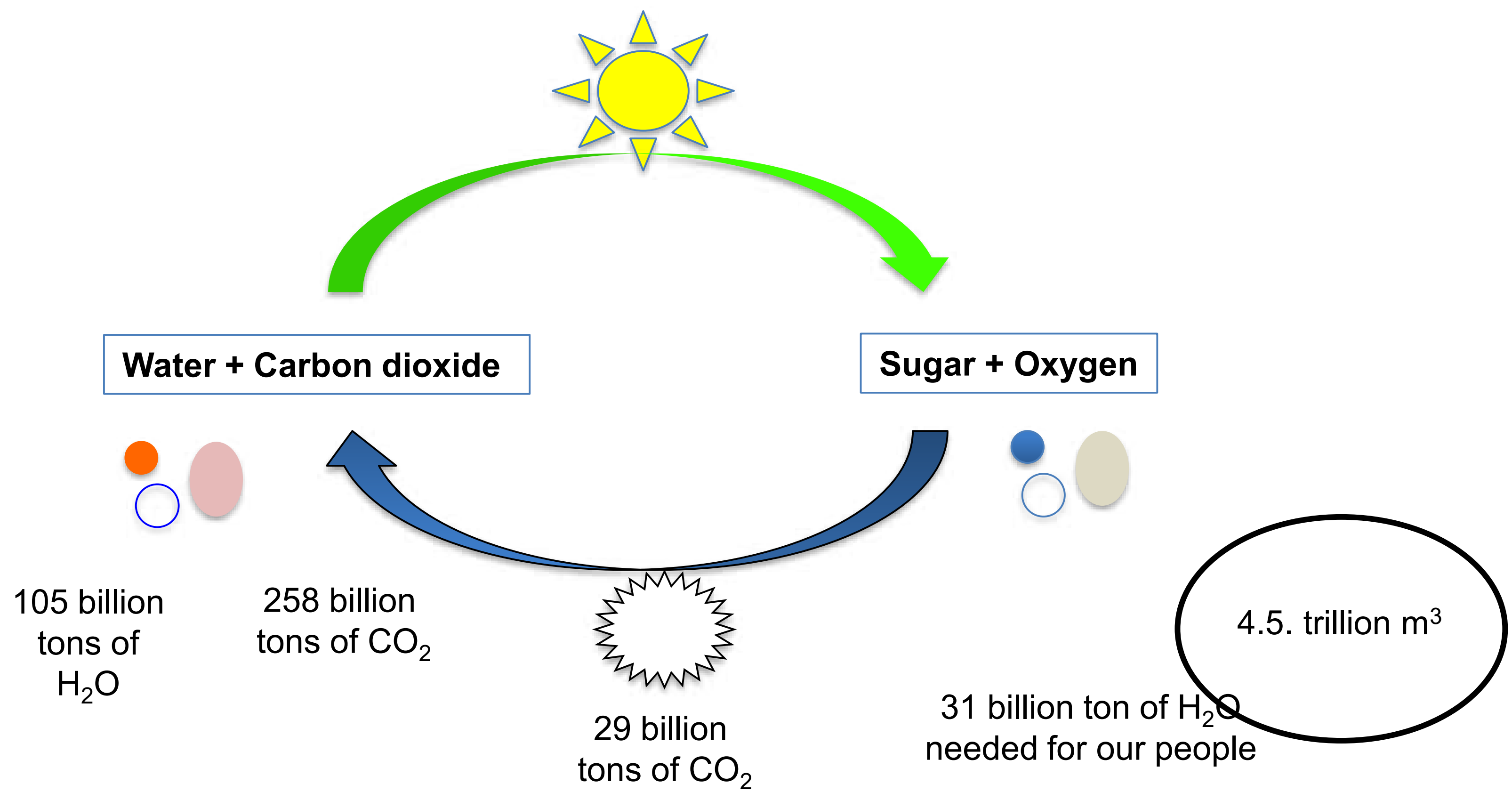


Wikipedia

Galileo Galilei 1589-92

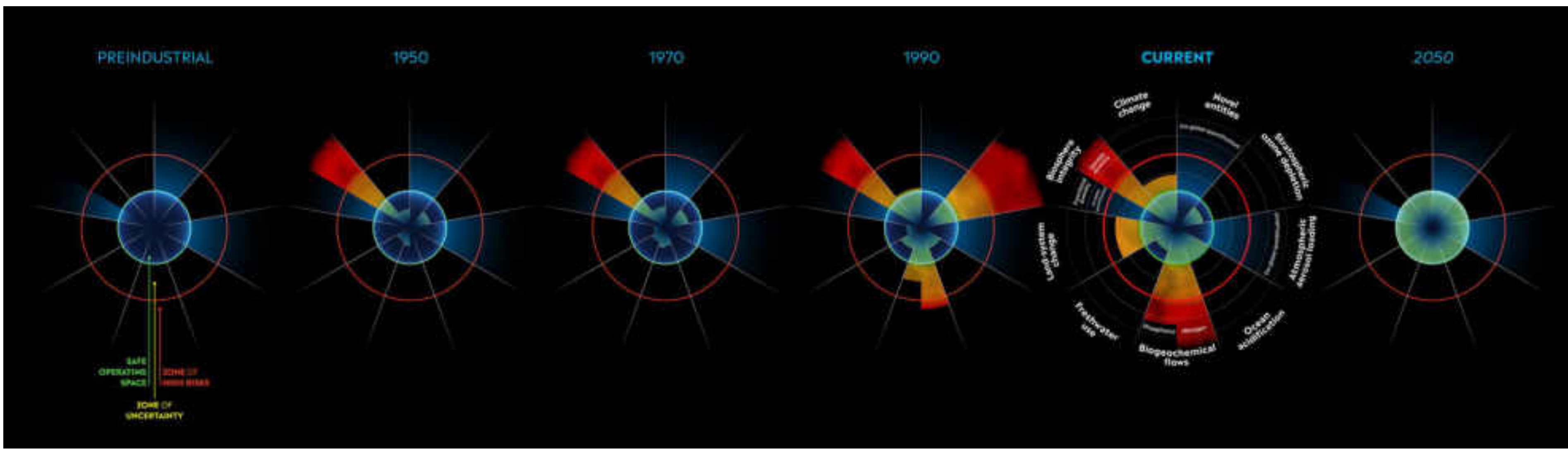

Interdependence
Reflection, heat conten
Melting, sea level rise
Biodiversity
…
….
Banking

We opened the cycle



Our restriction – confined space

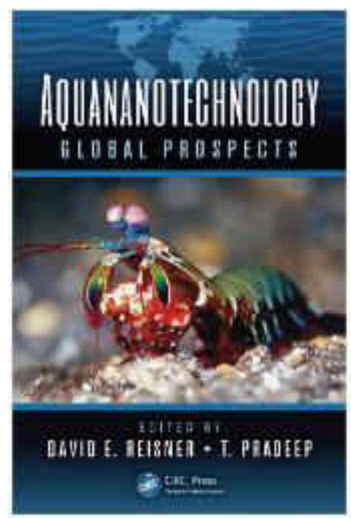
Planetary boundaries



https://globaia.org/planetary-boundaries

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

Scale of materials needed for water

“About two billion people worldwide don’t have access to safe drinking water today, and roughly half of the world’s population is experiencing severe water scarcity for at least part of the year.” - The UN

- Estimating the max. possible requirement of **Activated Alumina/ Aluminium Hydroxide**:

2 billion people × 3 litres/person/day × 50 mg/litre dosage (upper limit) =
300 billion mg/day, or, 300,000 metric tons/day, or **0.3 billion kg/day**

- In the case of **sand/activated carbon** (20 mg/l):

2 billion people × 3 litres/person × 20 mg/litre dosage = 120 billion mg, or **0.12 billion kg/day**

https://www.un.org/en/climatechange/science/climate-issues/water#:~:text=About%20two%20billion%20people%20worldwide,and%20population%20growth%20(WMO).

Biological complexity is built with just a few elements

https://blog.gale.com/celebrating-the-periodic-table/

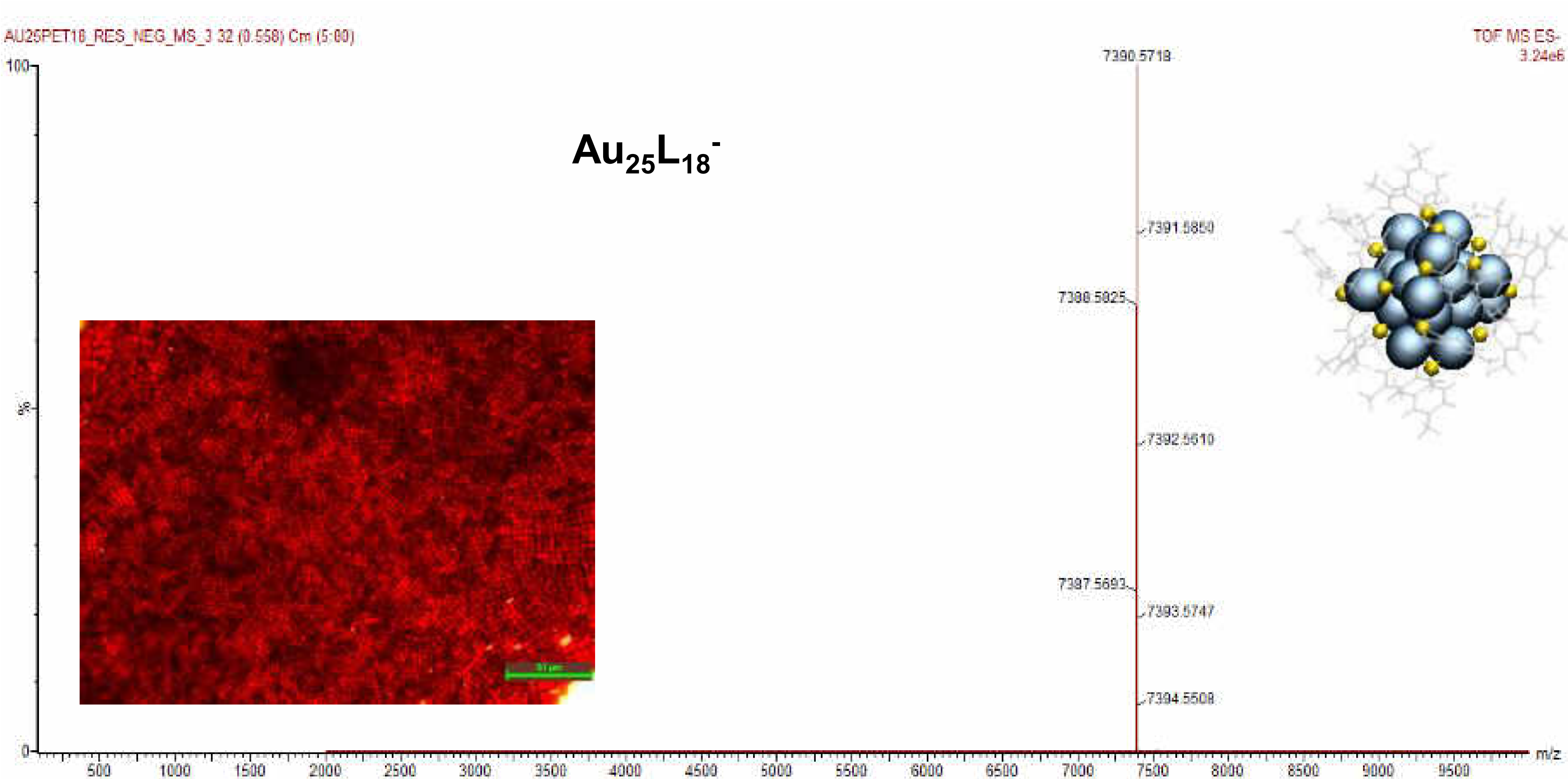
We developed environmentally friendly water positive nanoscale materials for affordable, sustainable and rapid removal of arsenic from drinking water.

There are over 1700 community installations across the country, serving 1.3 million people with arsenic and iron-free water every day.

Clean water for everyone

ACS Sustainable Chemistry & Engineering Editorial, December 2016

Nanomaterials are now atomically precise



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

Water positive materials

PNAS PNAS PNAS PNAS

Biopolymer-reinforced synthetic granular nanocomposites for affordable point-of-use water purification

Mohan Udhaya Sankar[1], Sahaja Aigal[1], Shihabudheen M. Maliyekkal[1], Amrita Chaudhary, Anshup, Avula Anil Kumar, Kamalesh Chaudhari, and Thalappil Pradeep[2]

Unit of Nanoscience and Thematic Unit of Excellen ... n, Chennai 600 036, India

Edited by Eric Hoek, University of California, Los A ... ved for review November 21, 2012)

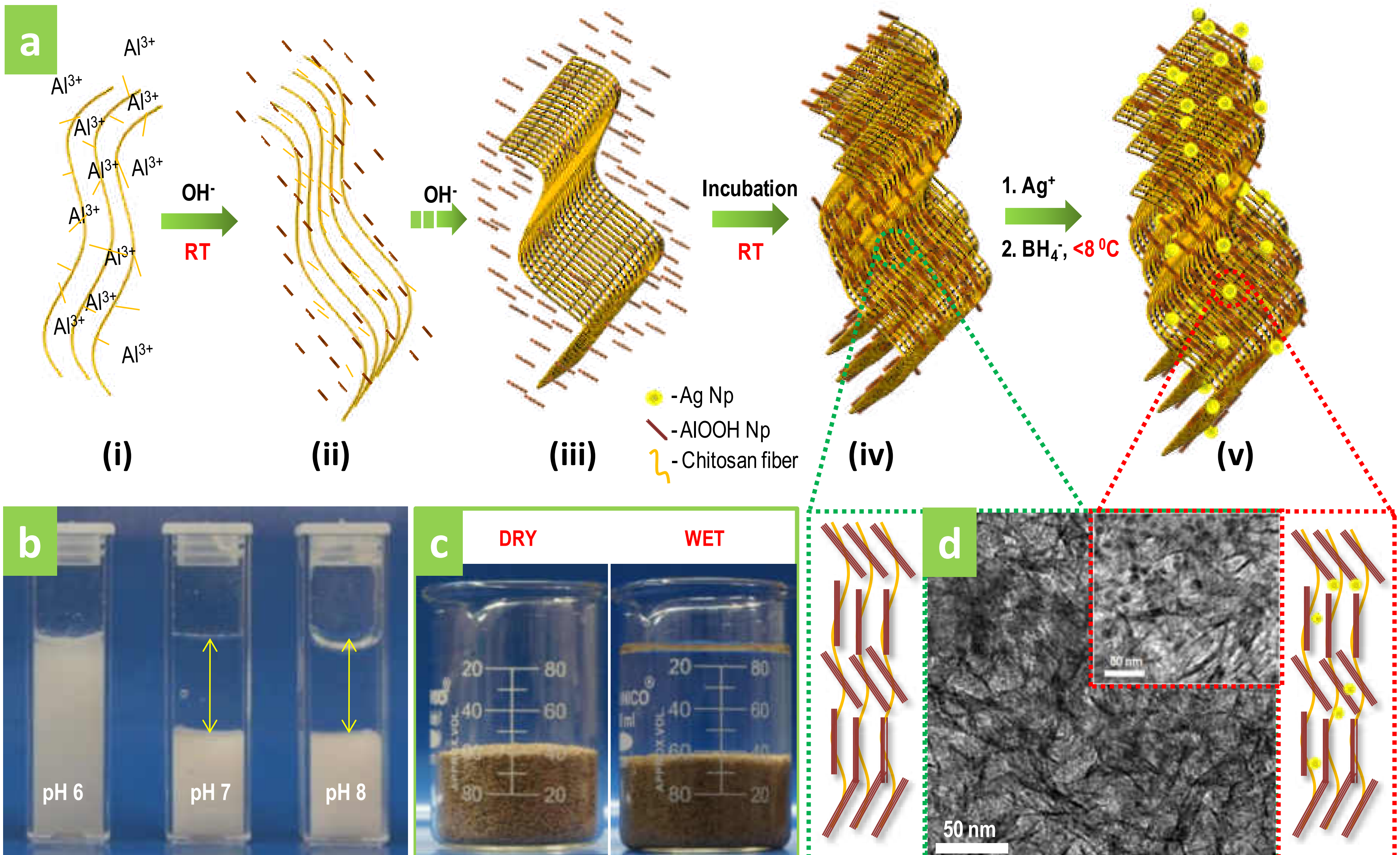
Creation of affordable materials for constant r
water is one of the most promising ways to pr
drinking water for all. Combining the capa
composites to scavenge toxic species such
other contaminants along with the above c
affordable, all-inclusive drinking water purif
without electricity. The critical problem in
synthesis of stable materials that can relea
uously in the presence of complex specie
drinking water that deposit and cause sca
surfaces. Here we show that such constant
be synthesized in a simple and effective fashio
out the use of electrical power. The nanoco
sand-like properties, such as higher shear stre
forms. These materials have been used to d
water purifier to deliver clean drinking water
ily. The ability to prepare nanostructured c
ambient temperature has wide relevance f
water purification.

ble; and (c) continued retention
ix is difficult.
unique family of nanocrystalline
nular composite materials pre-
through an aqueous route. The
ition is attributed to abundant -O-
hitosan, which help in the crys-
and also ensure strong covalent
ace to the matrix. X-ray photo-
irms that the composition is rich
sing hyperspectral imaging, the
g in the water was confirmed.
activate the silver nanoparticle
timicrobial activity in drinking
have been developed that can
water. We demonstrate an af-
e based on such composites de-
dergoing field trials in India, as
d eradication of the waterborne
disease burden.

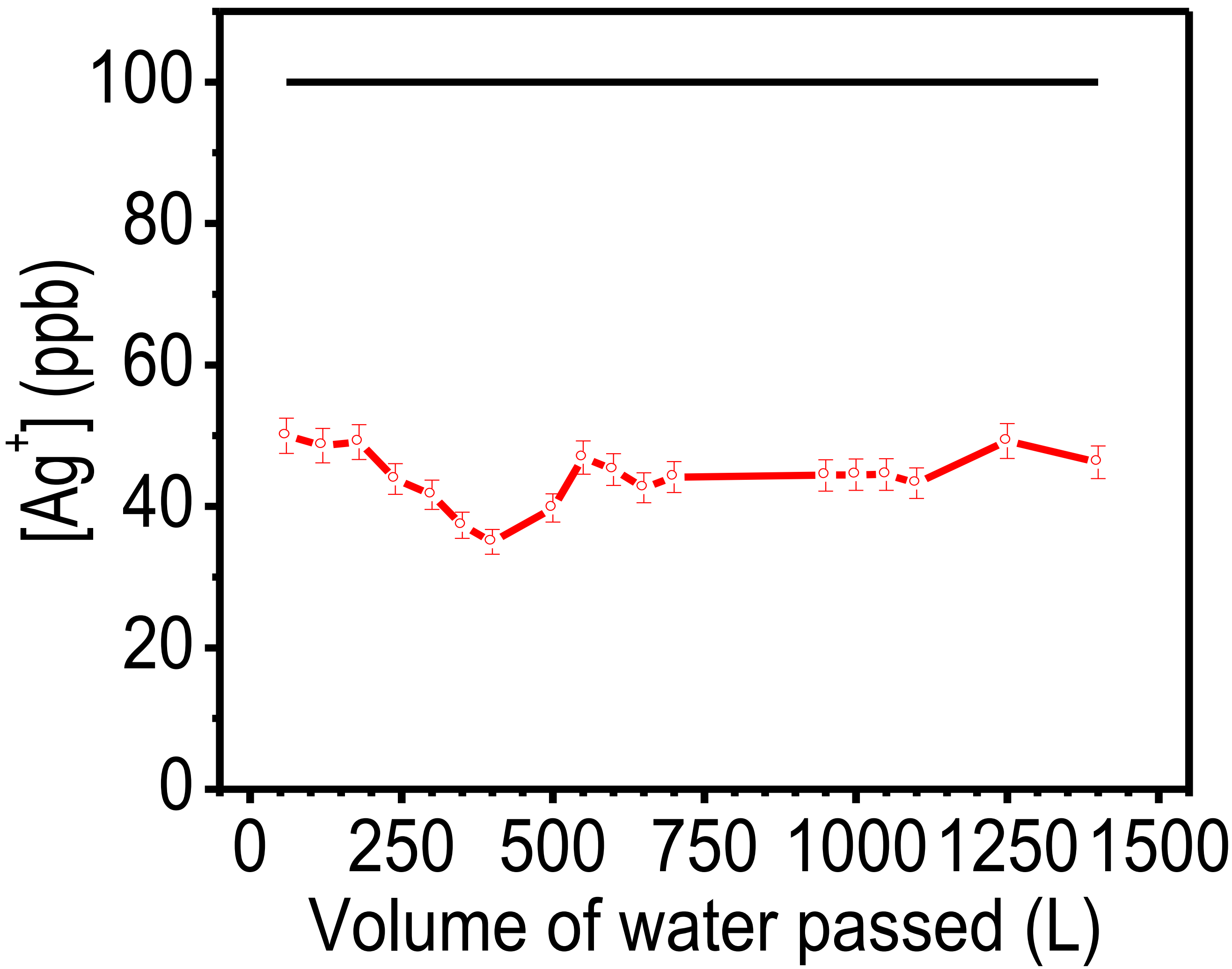
hybrid | green | appropriate technology | frugal science | developing world

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

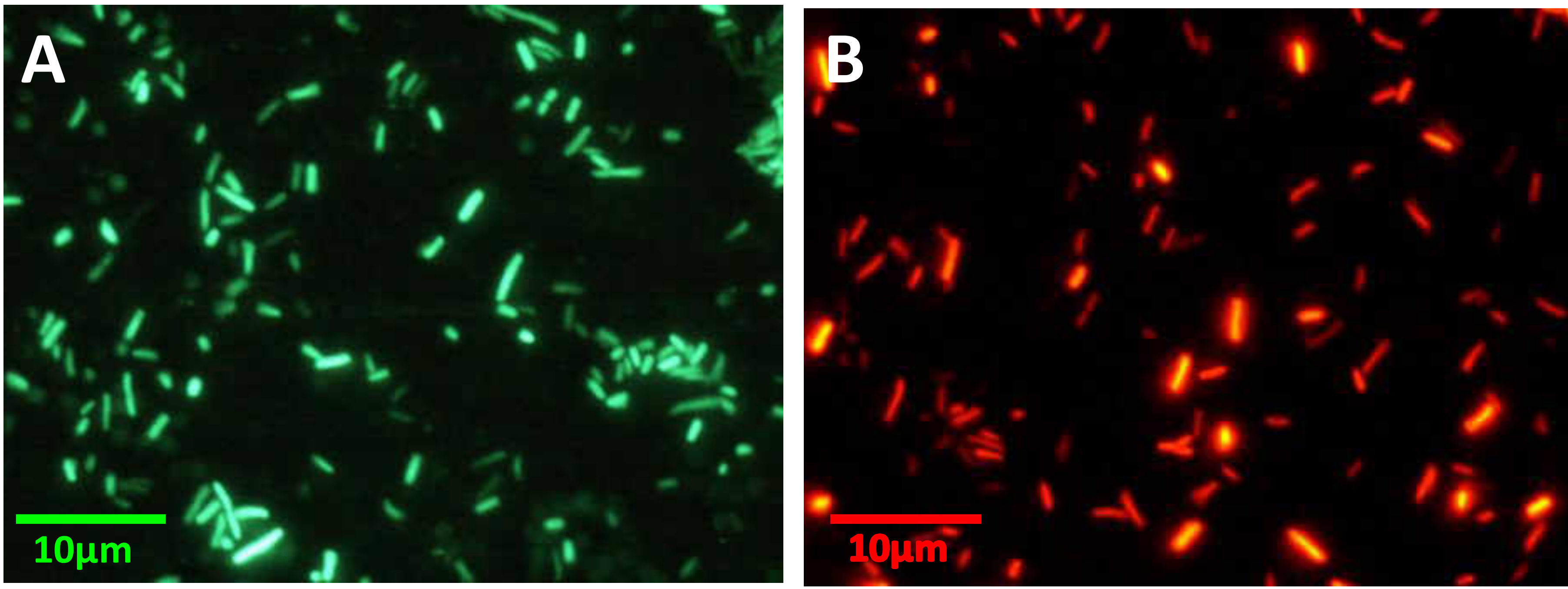
How to make?


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

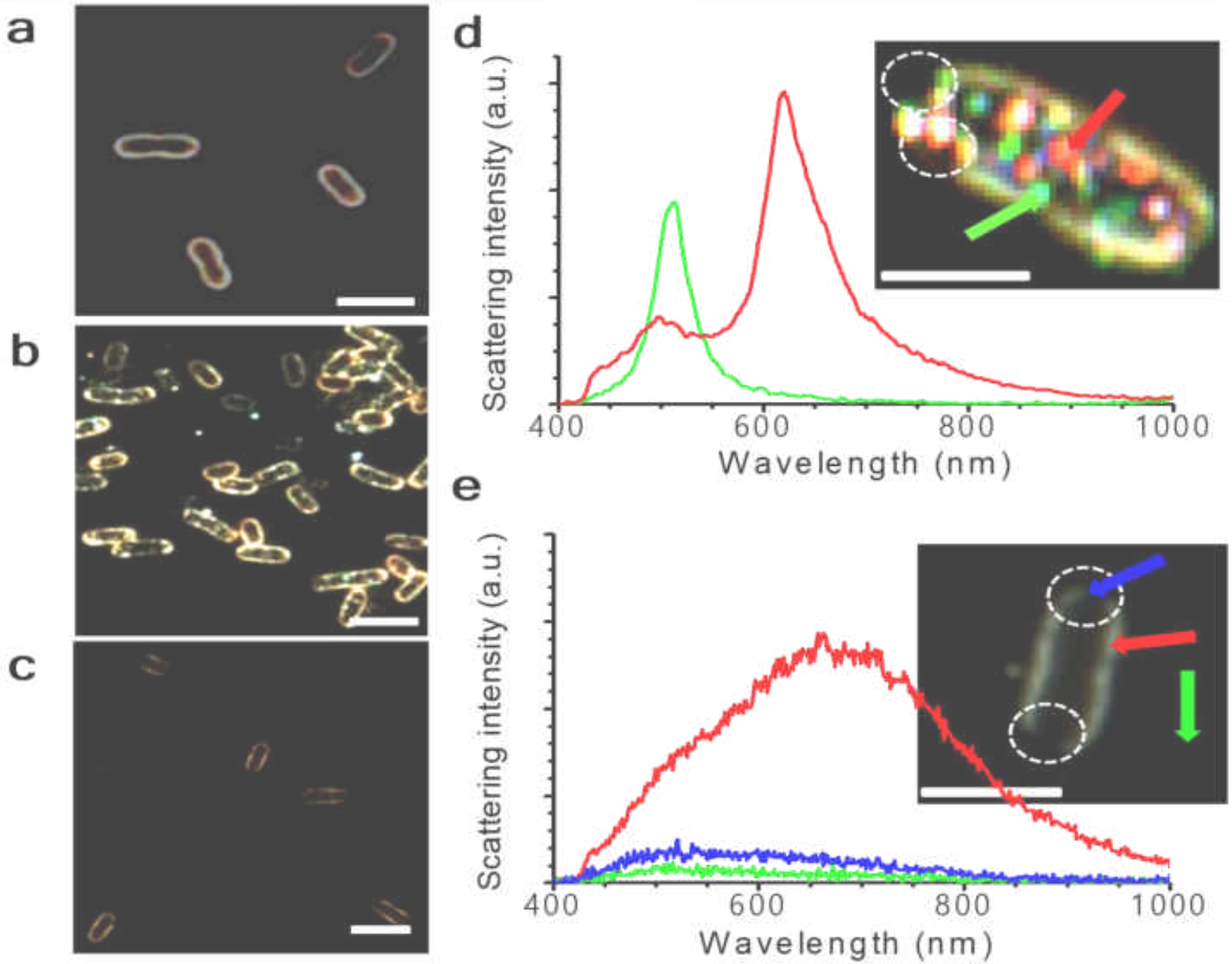
What is special?



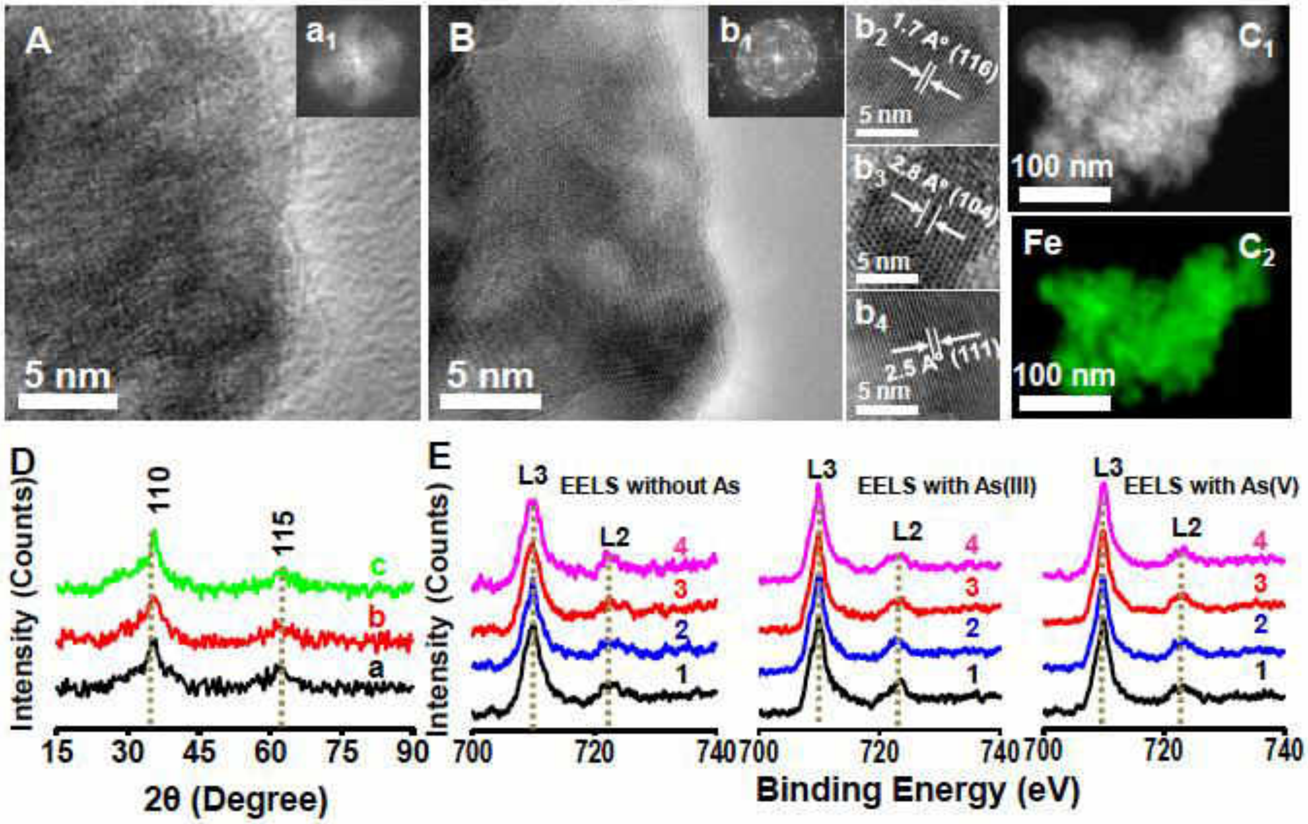
Live/dead staining experiments



No nanotoxicity



Variety of materials



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

Author Proof

ADVANCED MATERIALS

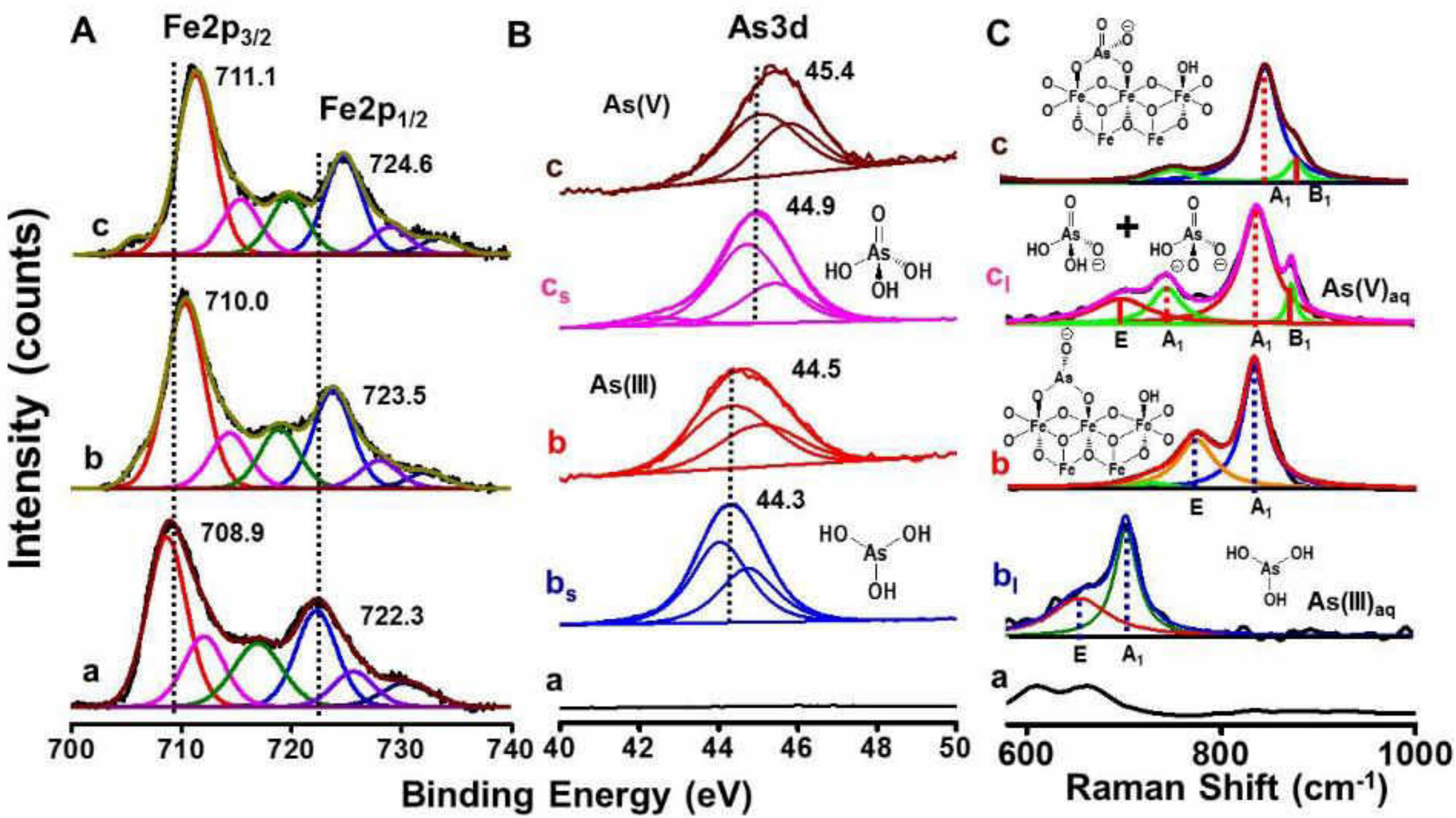
www.advmat.de

Communication

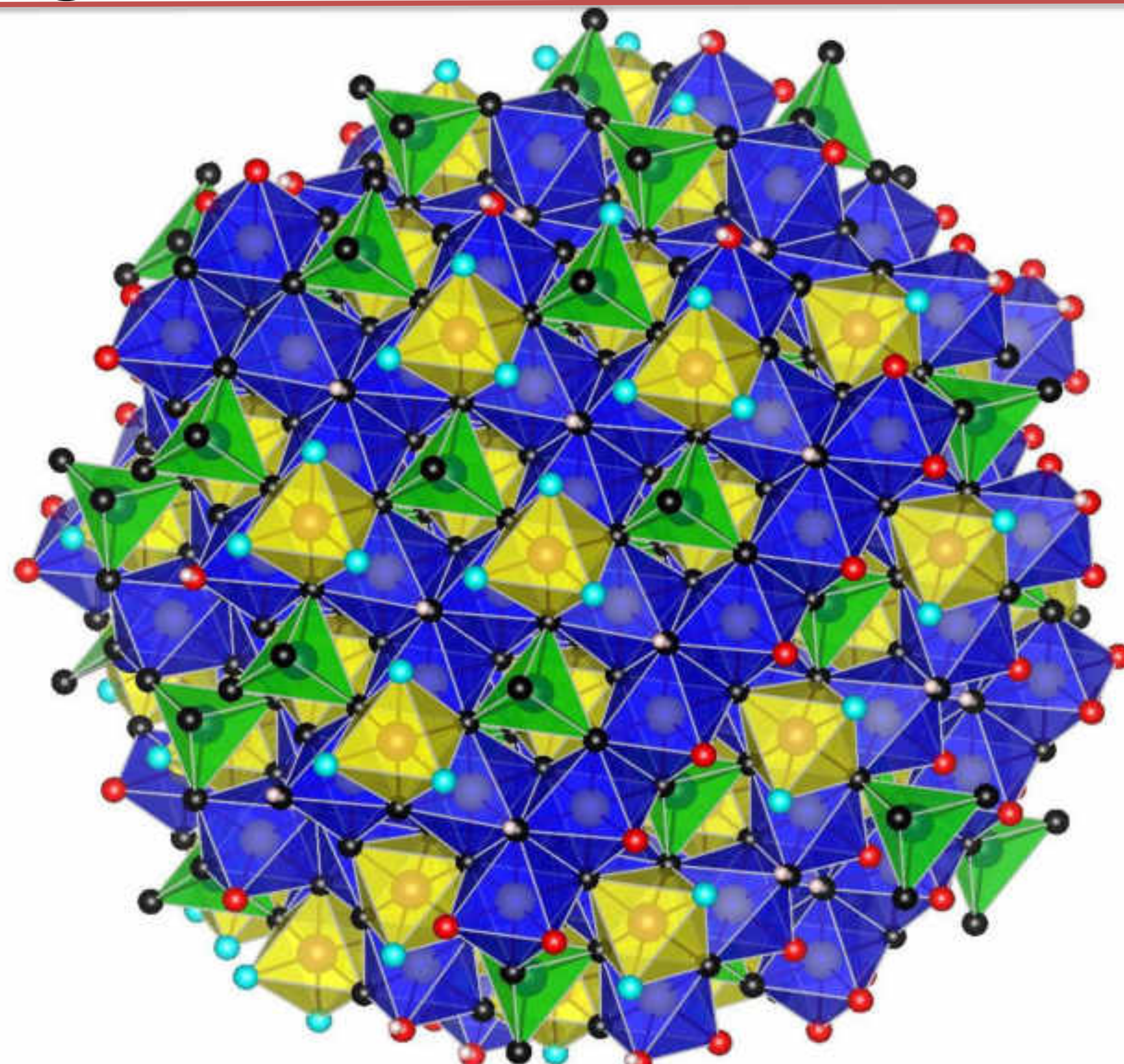
Confined Metastable 2-Line Ferrihydrite for Affordable Point-of-Use Arsenic Free Drinking Water

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**

Mechanism

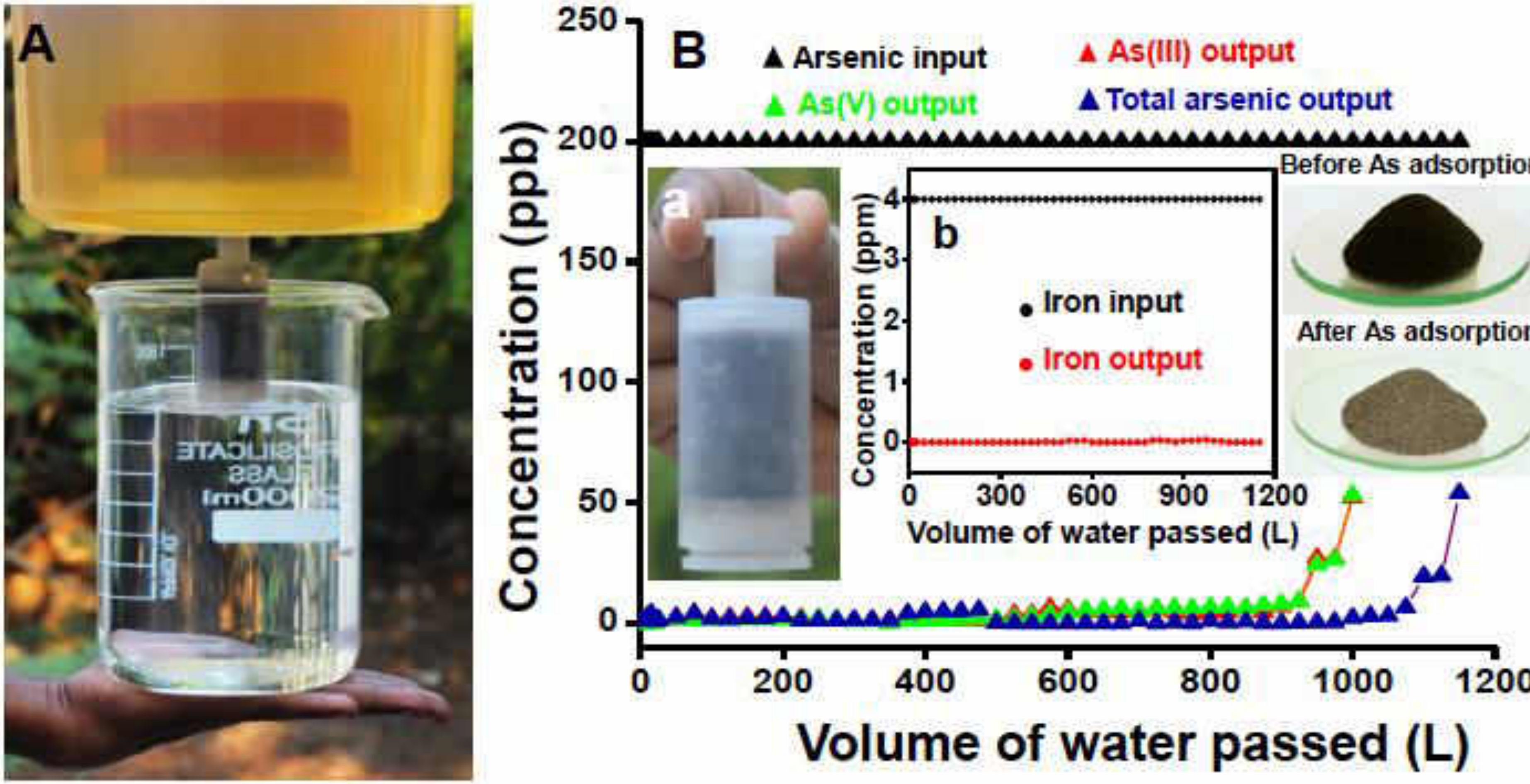

A
Fe2p3/2
711.1
Fe2p1/2
724.6
710.0
723.5
708.9
722.3
c
b
a
Intensity (counts)
B
As3d
As(V)
45.4
c
44.9
cs
As(III)
44.5
b
44.3
bs
a
HO
OH
As
C
c
A1
B1
cl
As(V)aq
E
b
bl
As(III)aq
Binding Energy (eV)
Raman Shift (cm-1)
700
710
720
730
740
40
42
44
46
48
50
600
800
1000

Modeling surfaces



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

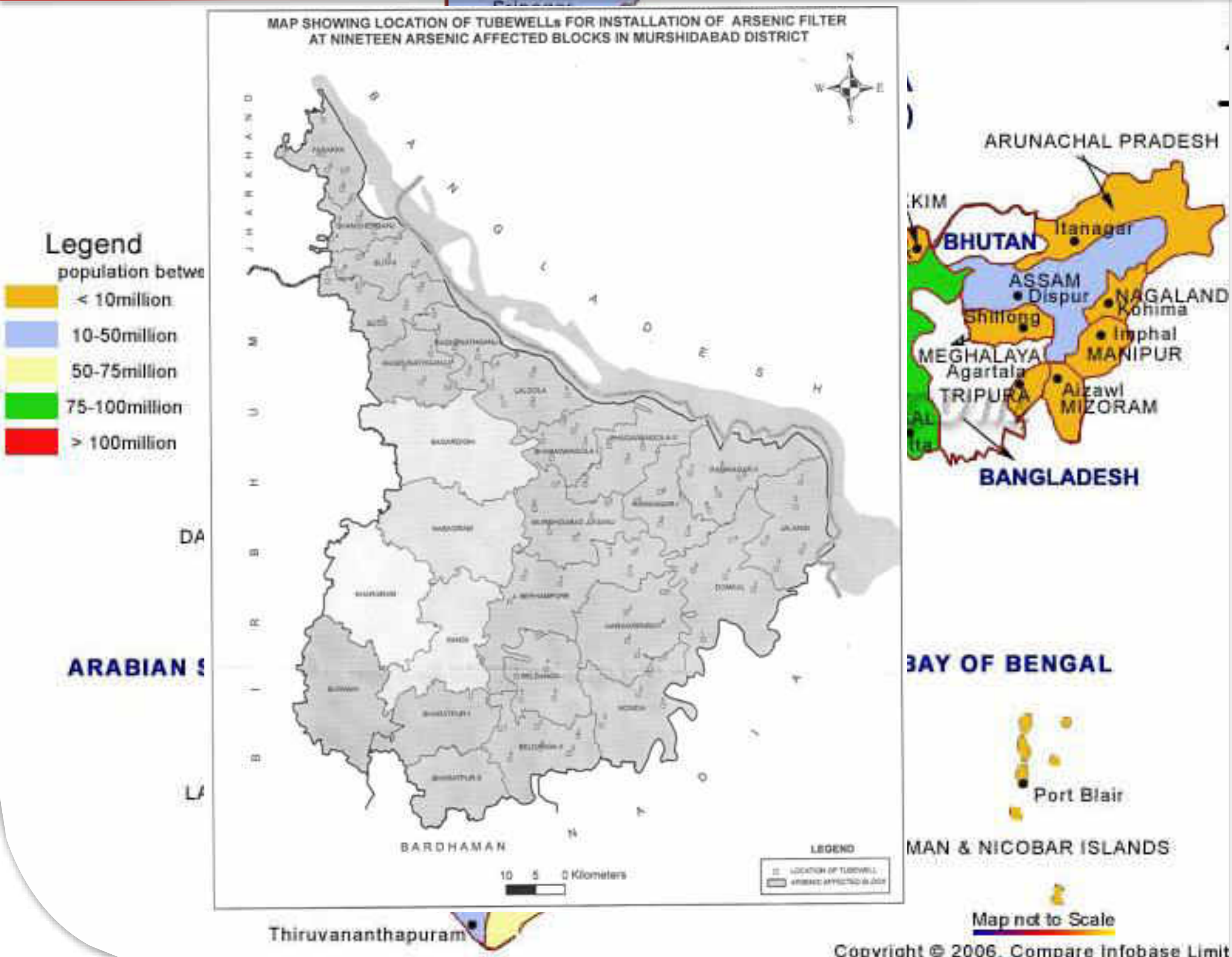
Lab studies



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

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

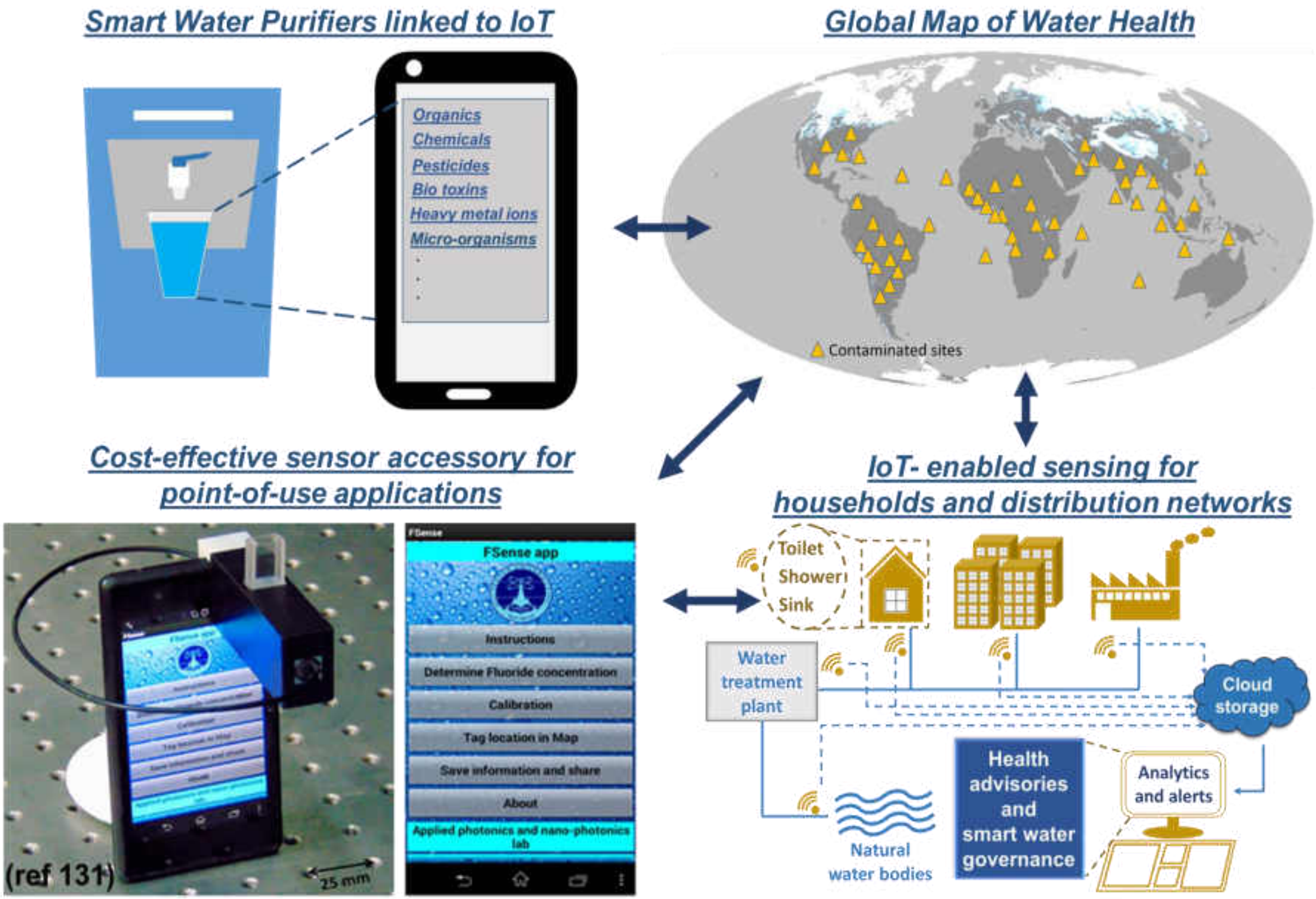
Across the country

Cleanwater at 2.1 paise per litre!

Calculation for the Tariff to be collected for treated water (Revision if Required)

Sr.No.	**Item/Description**	**Cost / Quantity**	**Remarks**
	Design population	1,071	Plant capacity/70 LPCD
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

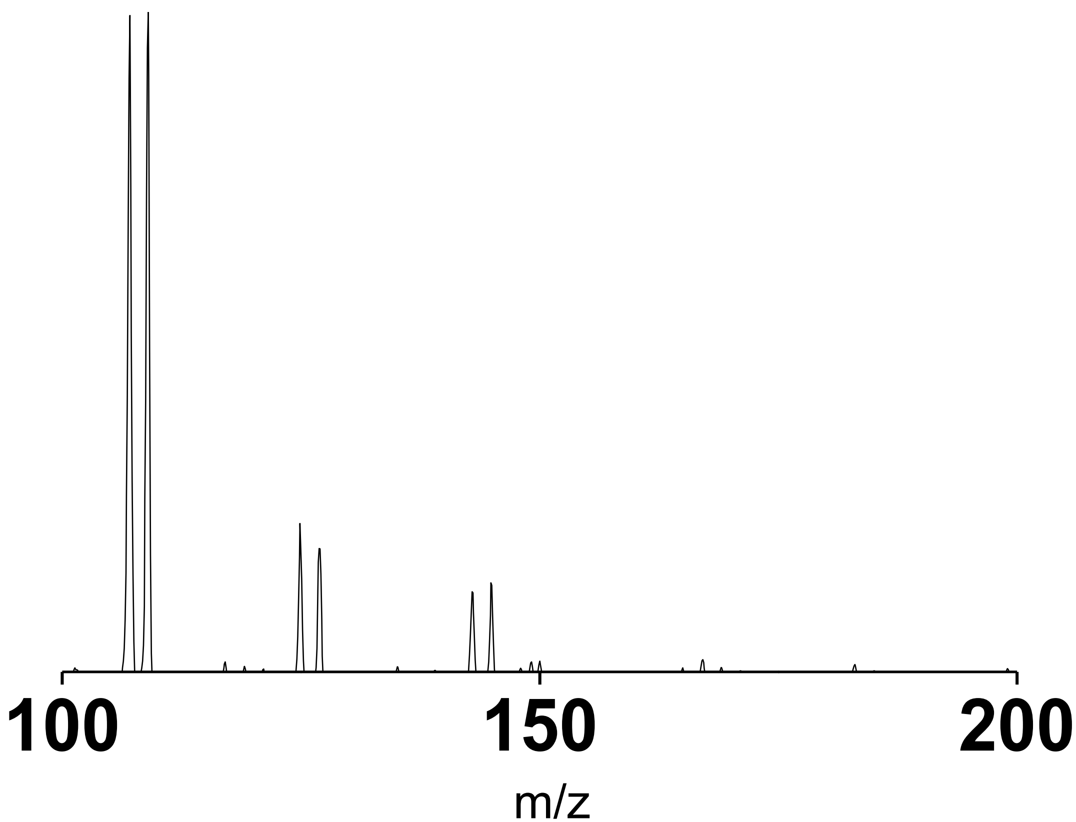
Elemental waste goes back to local environment

Safe disposal of arsenic (or any other) laden waste

Additional protection could be considered, if necessary

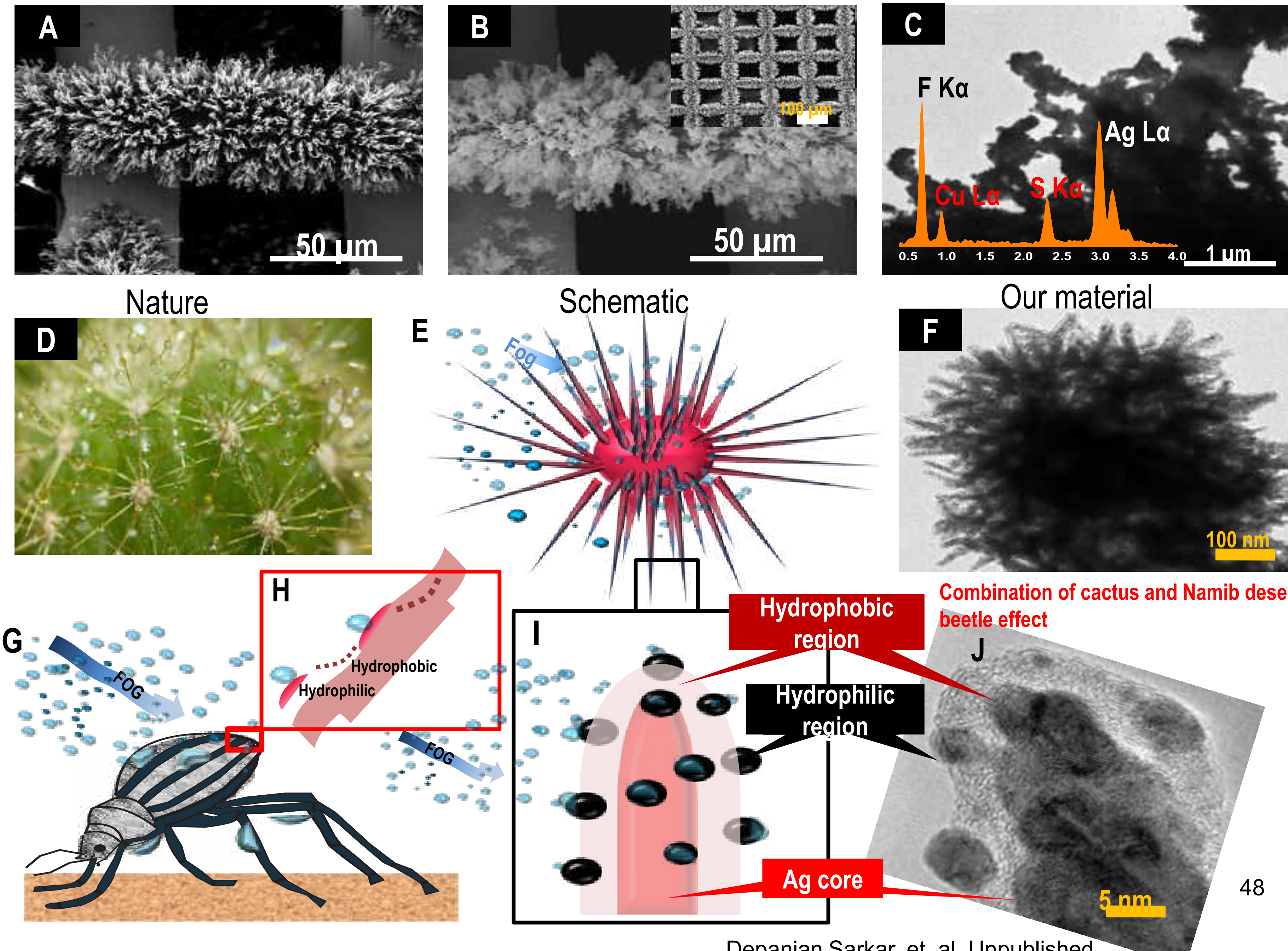
Exploring viable uses

Atmospheric water harvesting

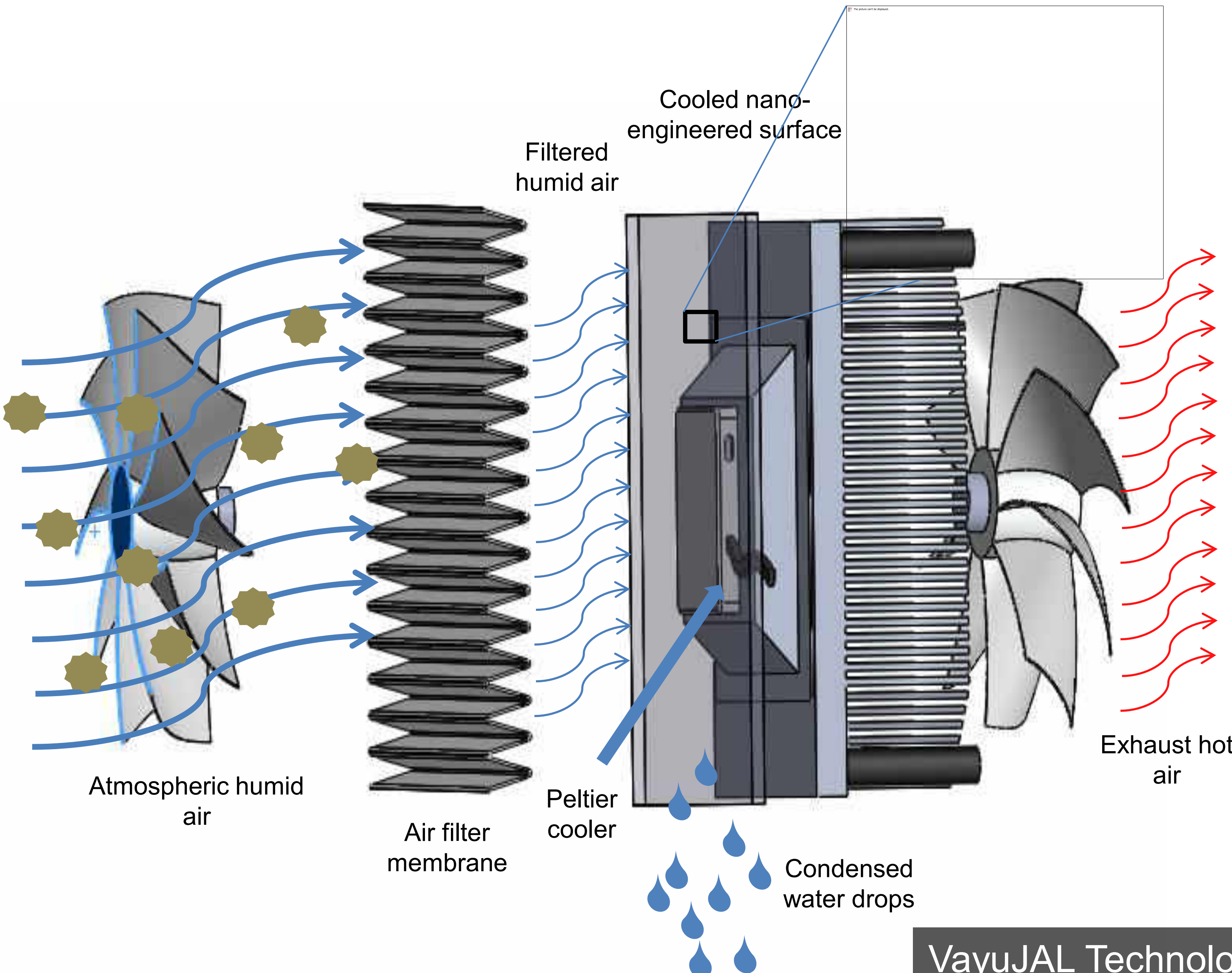


New harvesters

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



Depanjan Sarkar, et. al. Unpublished.



VayuJAL Technologies Pvt. Ltd.

Ramesh Kumar Soni and Ankit Nagar

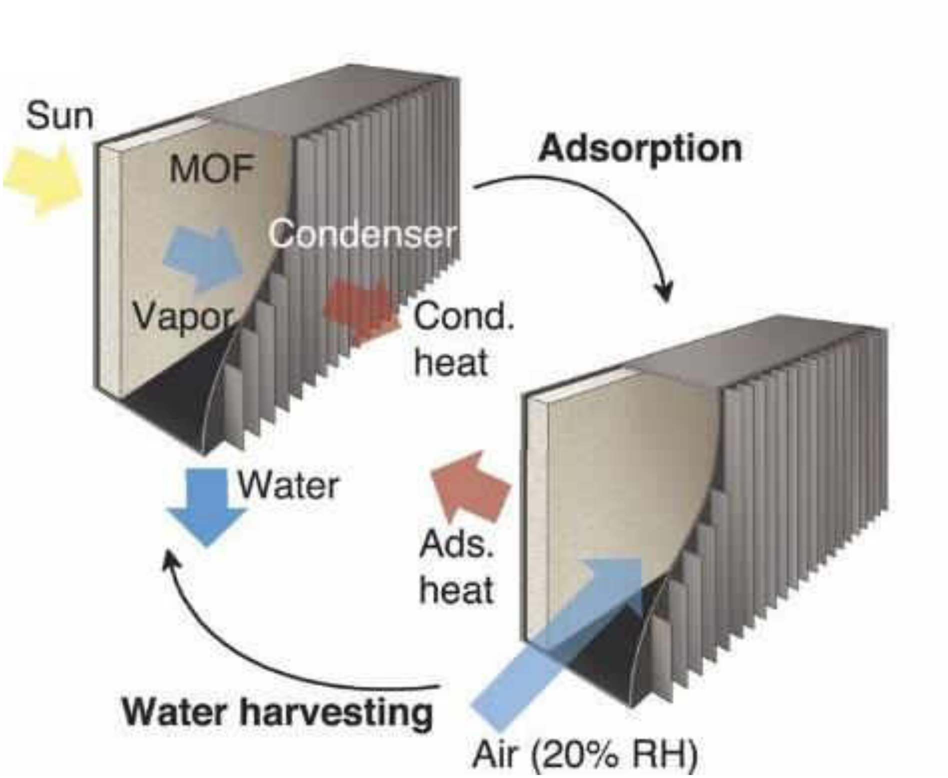
Products in the field

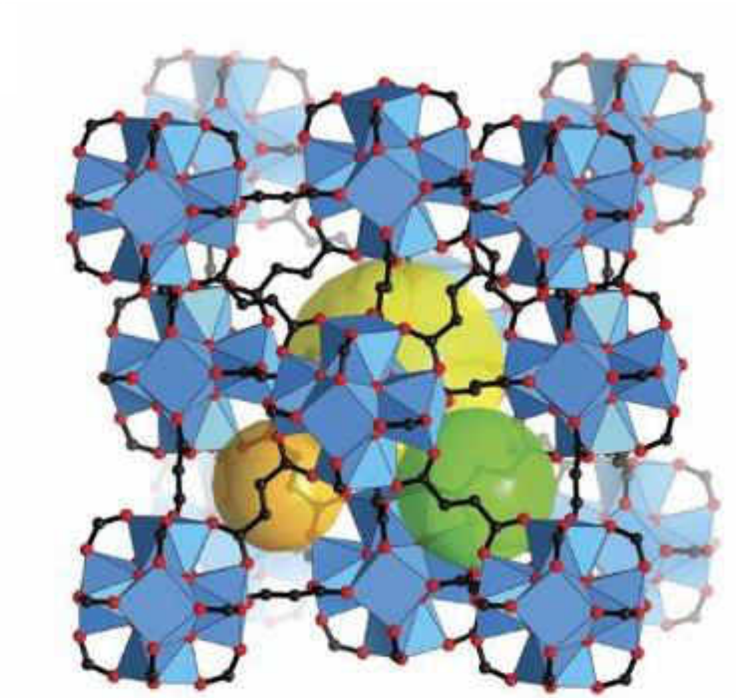
35 LPD 120 LPD 400 LPD 1000 LPD 2000 LPD

(LPD: Litres per day)

Sustainable atmospheric water harvesting

Solar- heat-enabled atmospheric water capture at a relative humidity as low as 20%

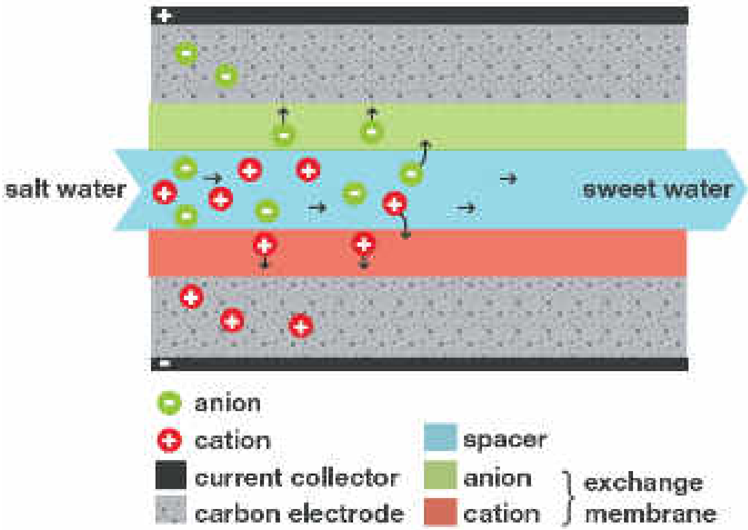


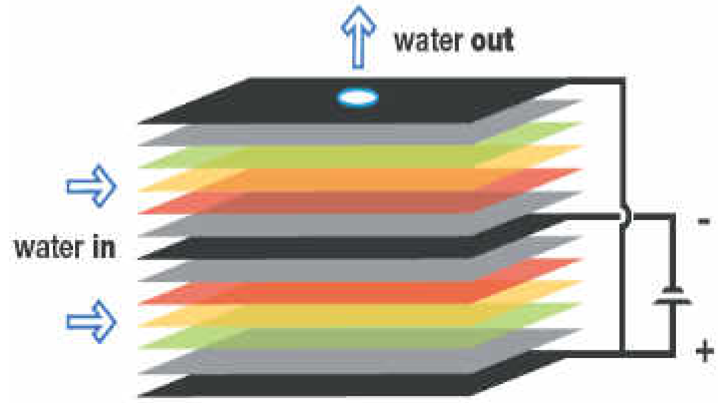


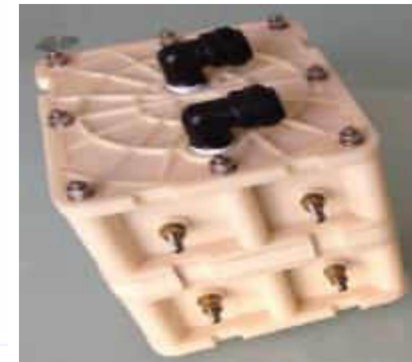
Porous metal-organic framework (MOF-801, $Zr_6O_4(OH)_4(fumarate)_6$)

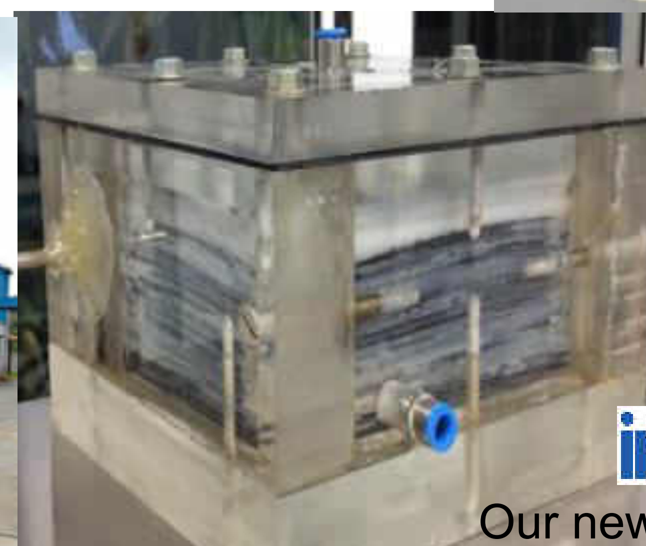
Kim Hyunho, et al. *Science,* 356 (6336) 2017

Capacitive Desalination (CDI)



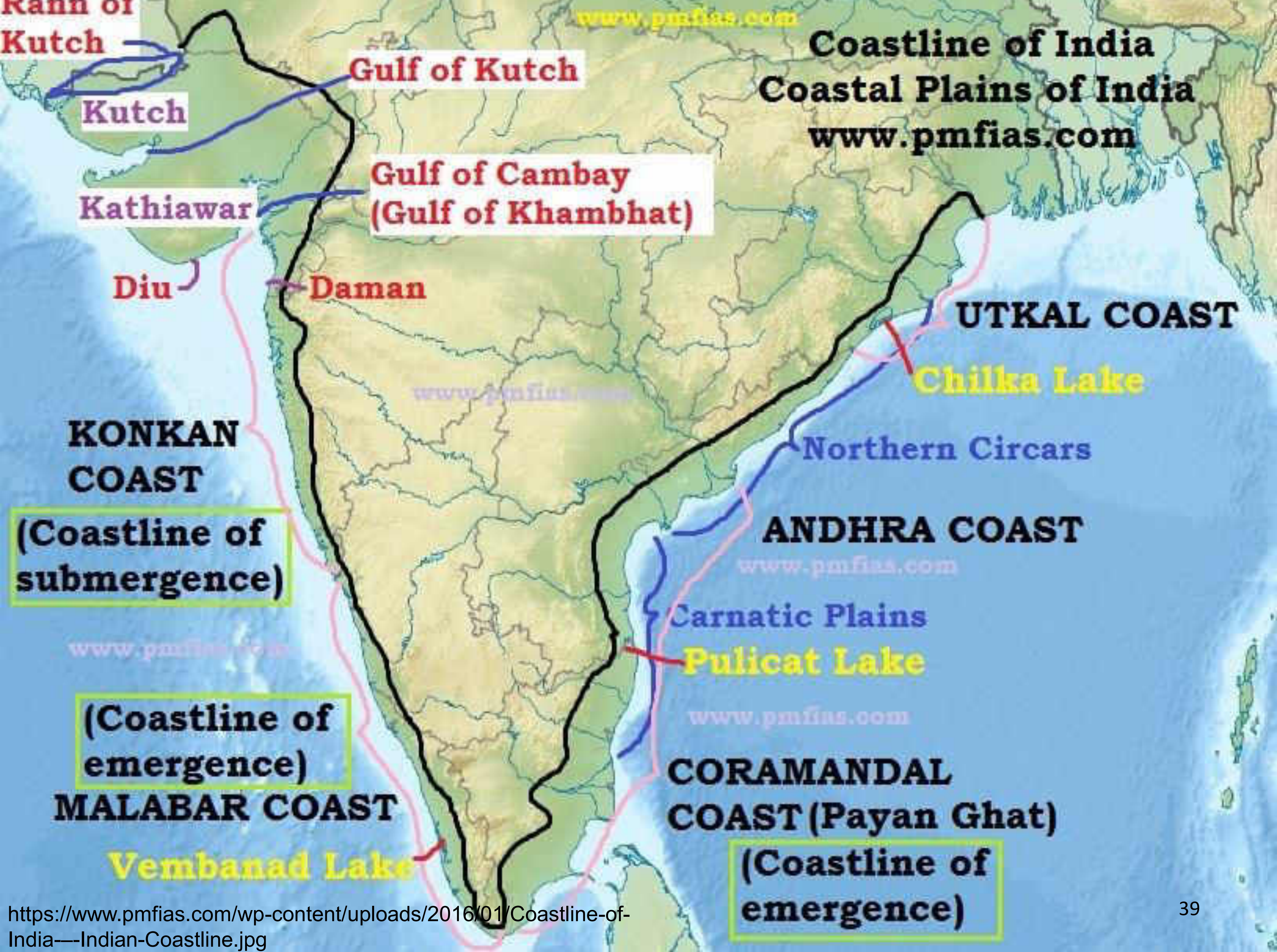




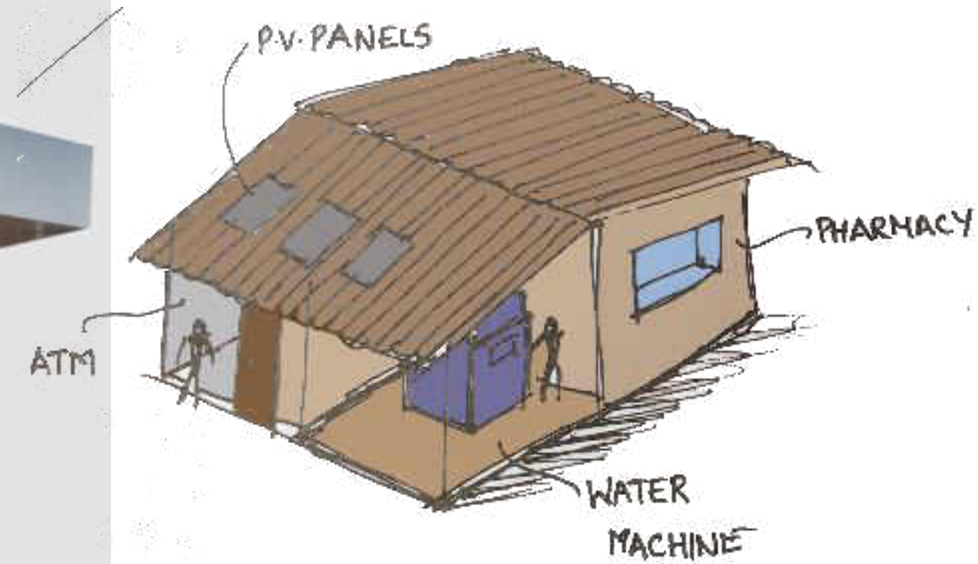


Our new company

Soujit Sengupta, Rabiul Islam and others



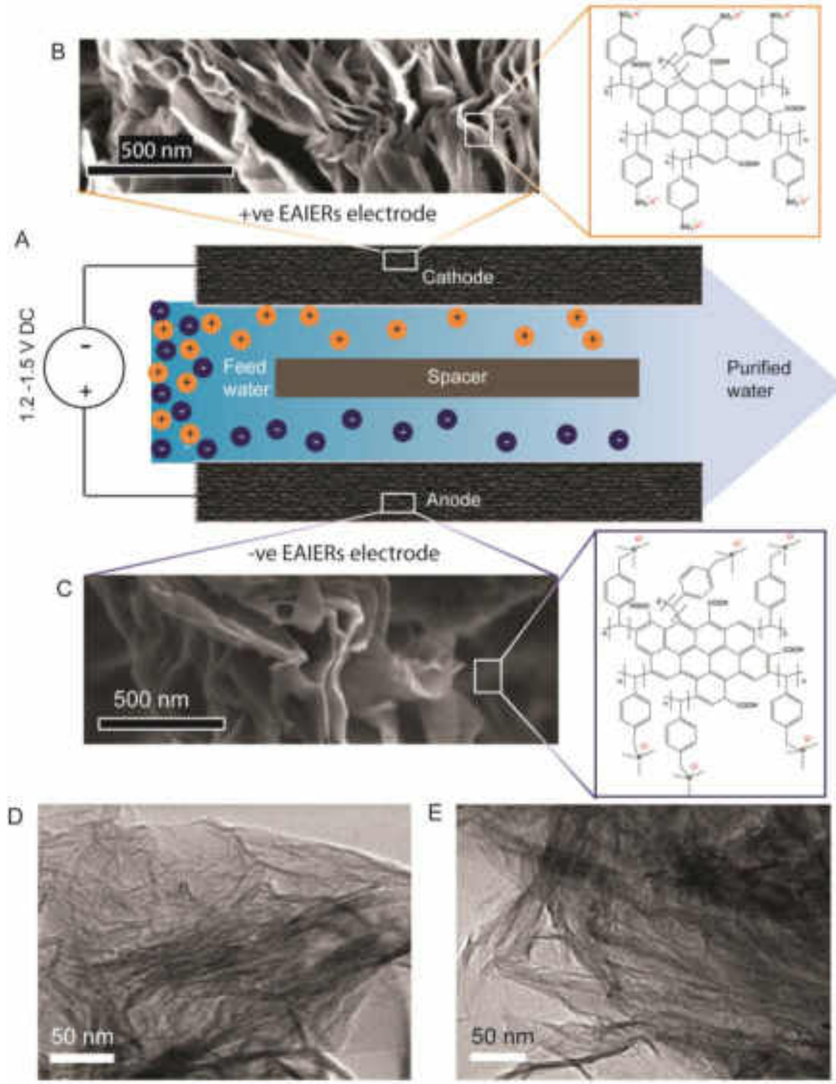
https://www.pmfias.com/wp-content/uploads/2016/01/Coastline-of-India-—-Indian-Coastline.jpg



Products under implementation

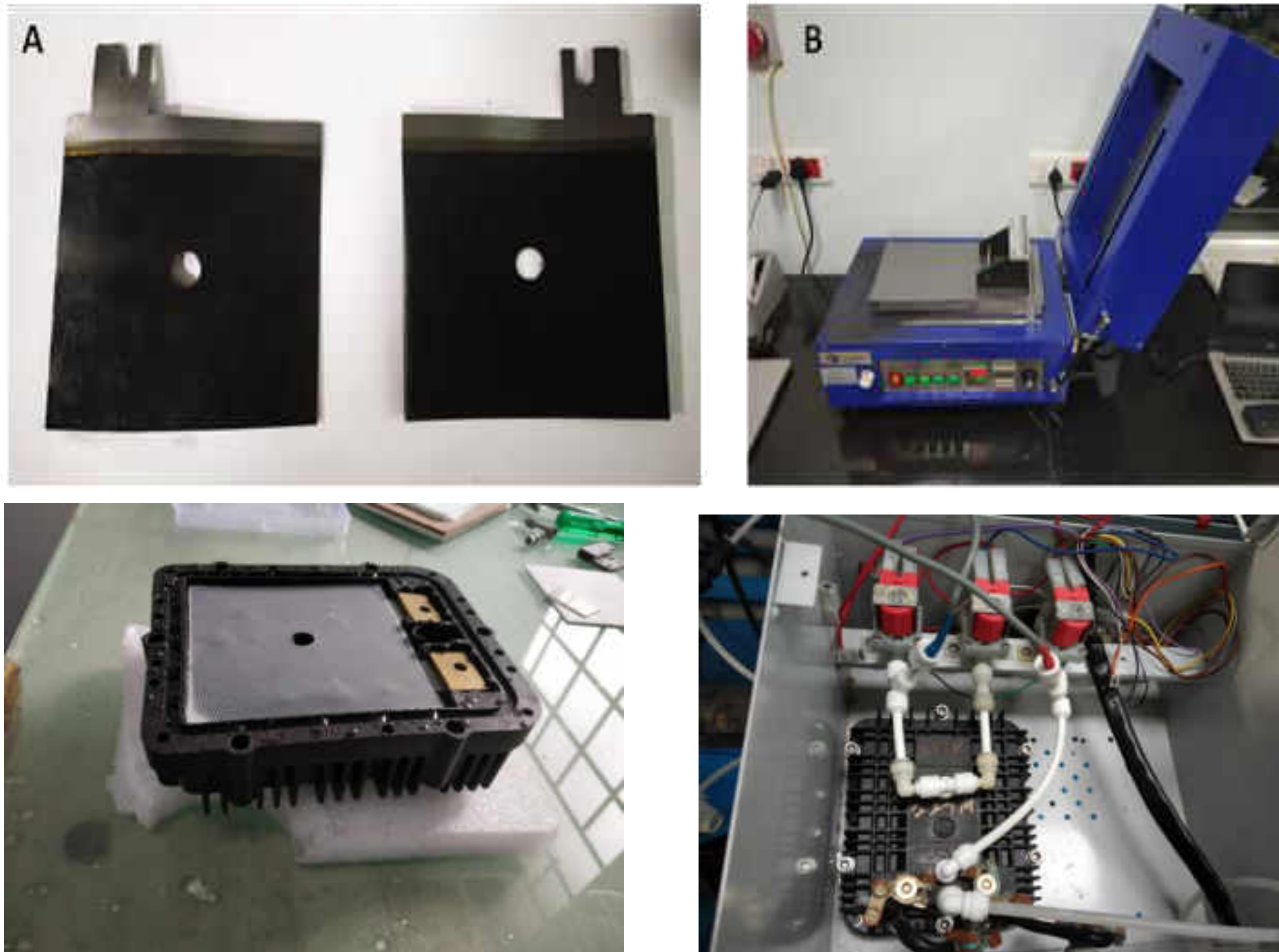
Vijay Sampath and Tullio Servida

A Covalently Integrated Reduced Graphene Oxide -Ion Exchange Resin Electrode for Efficient CDI

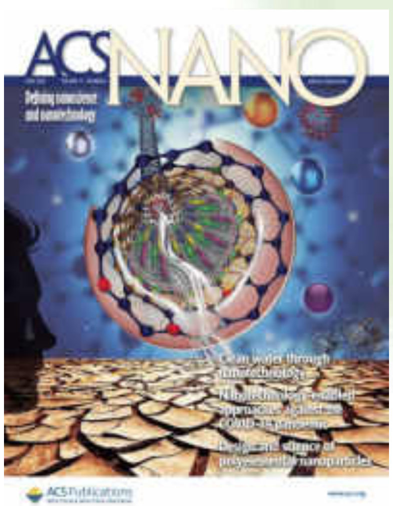


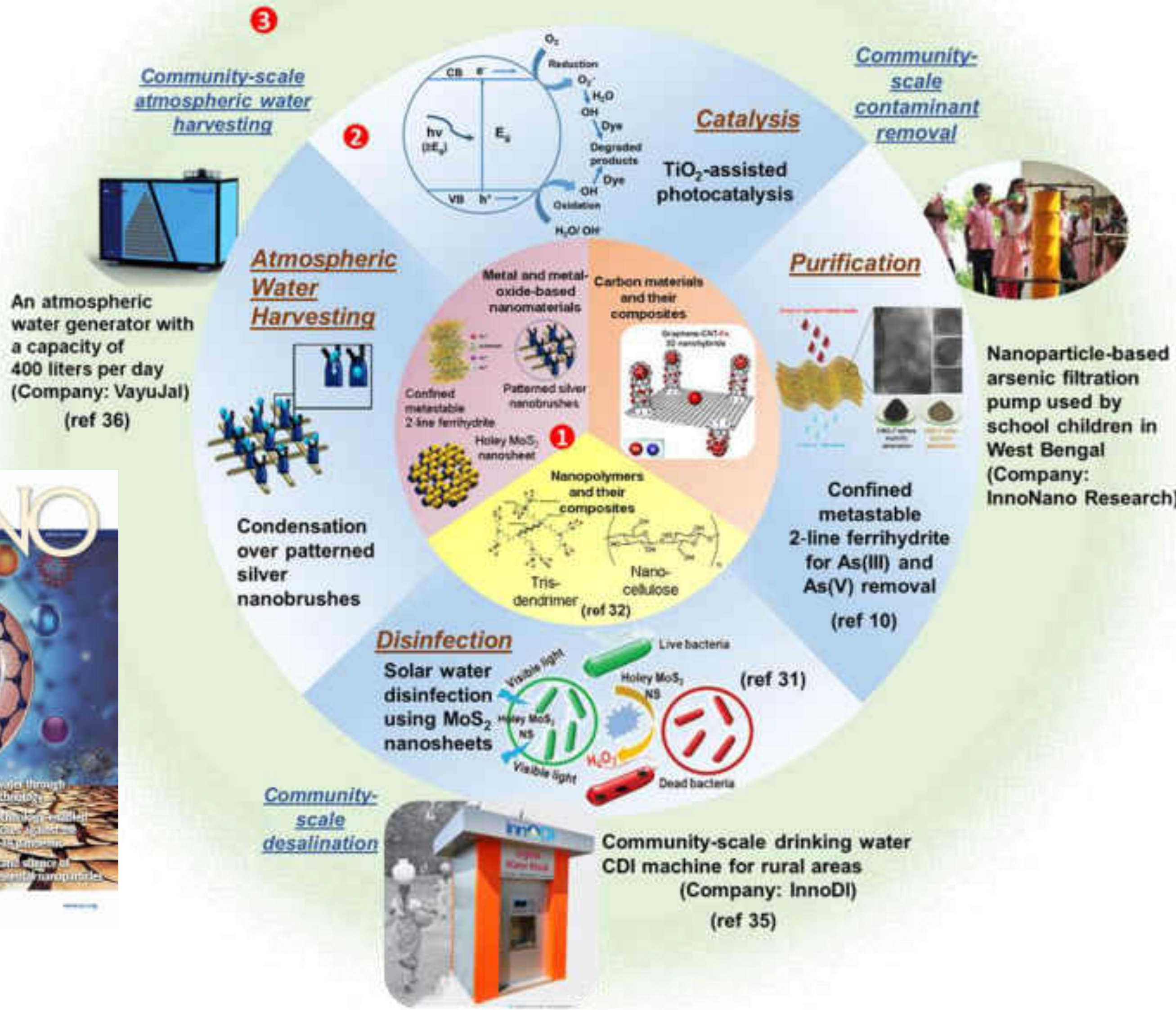
Rabiul *et al., Adv. Mater. Interfaces* **2021**, *8,* 2001998

Various stages of electrode preparation



Evolution of materials to products





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

Sensors and new opportunities

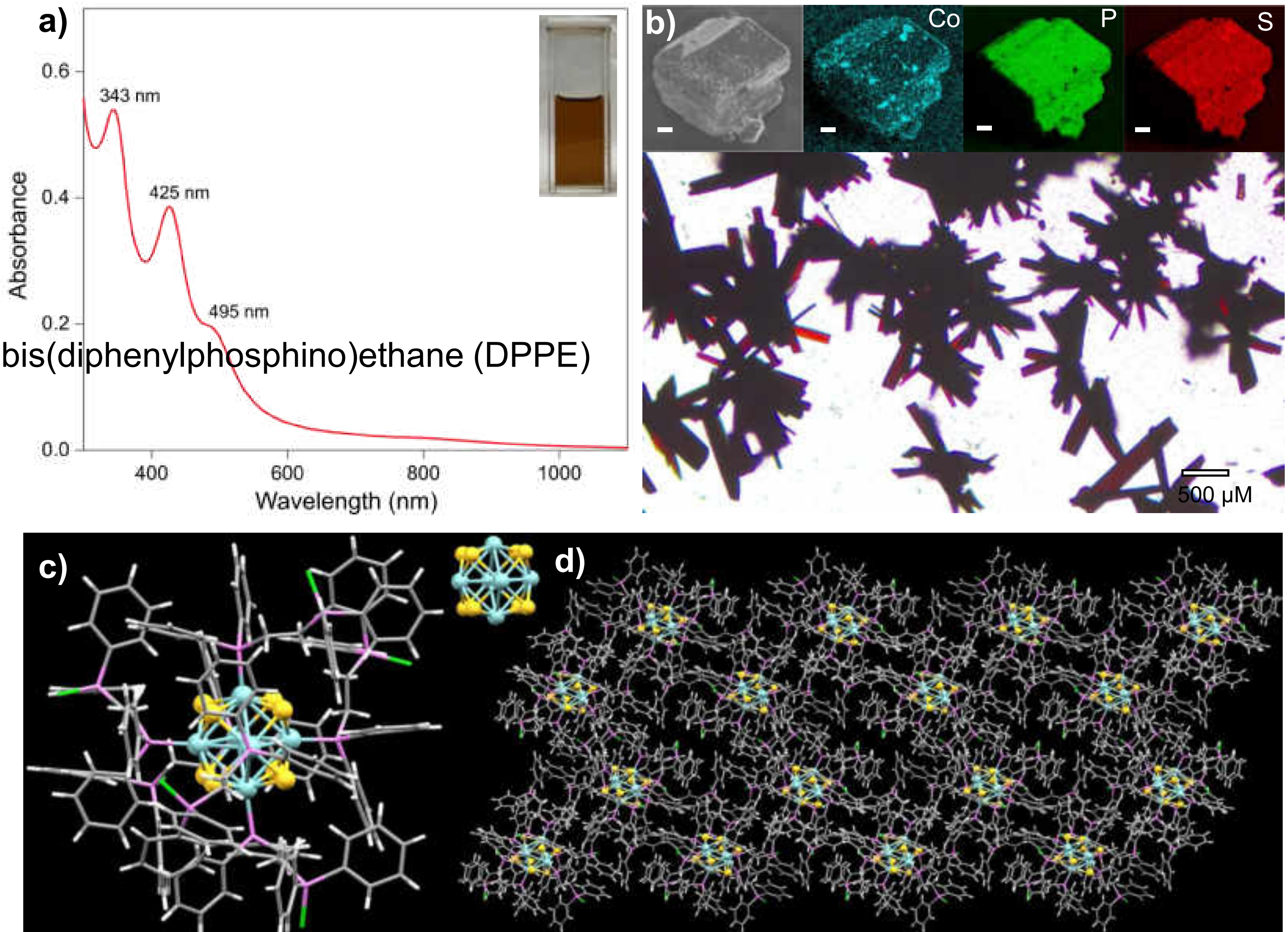
Analog/Grating
Equipment
$ 5~6 Billion (2017)
a few **100k units (2017)**

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

Water quality measurement – In the pipeline

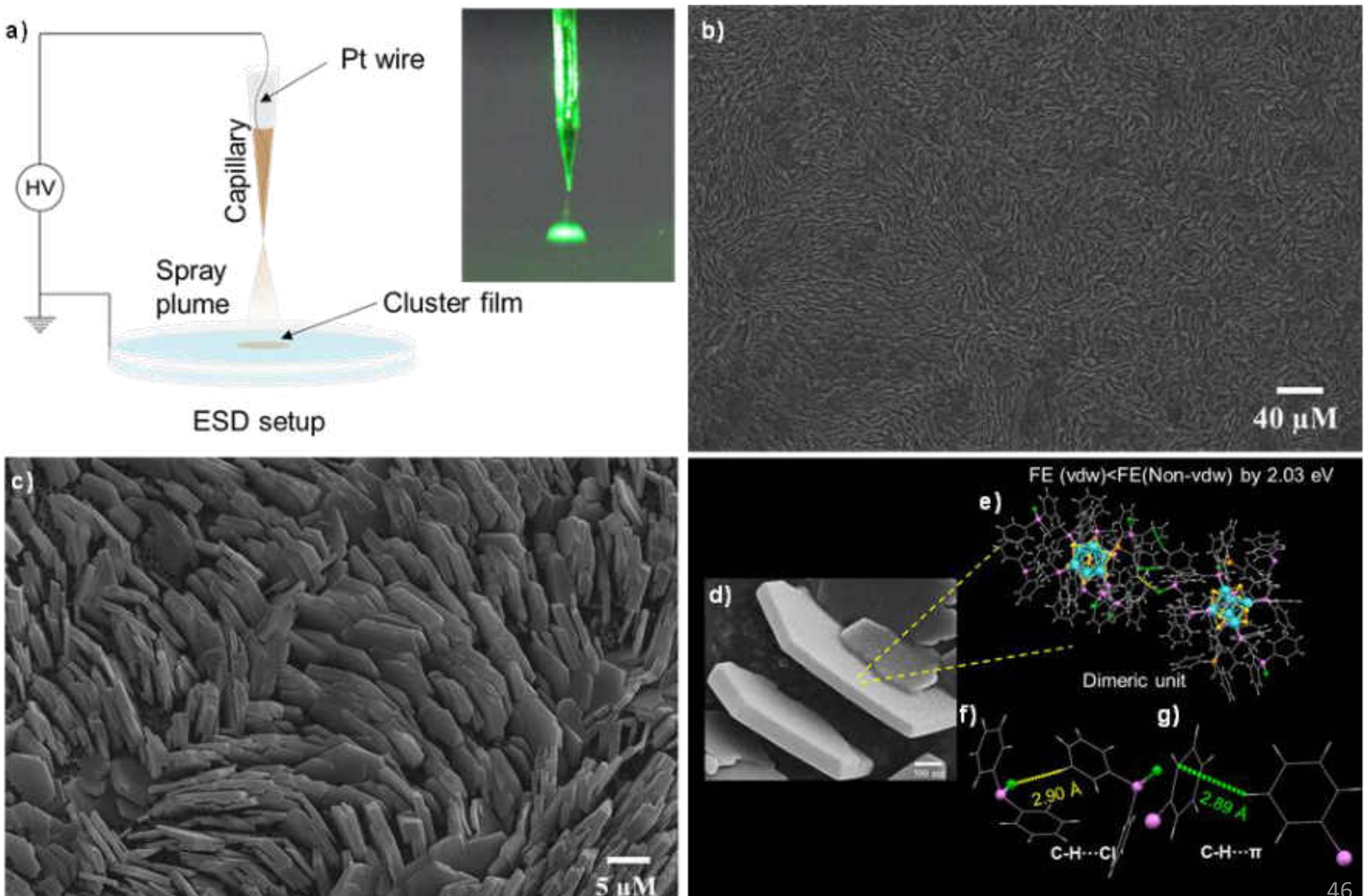
nanoλ

New electrodes - Aligned nanoplates of Co_6S_8

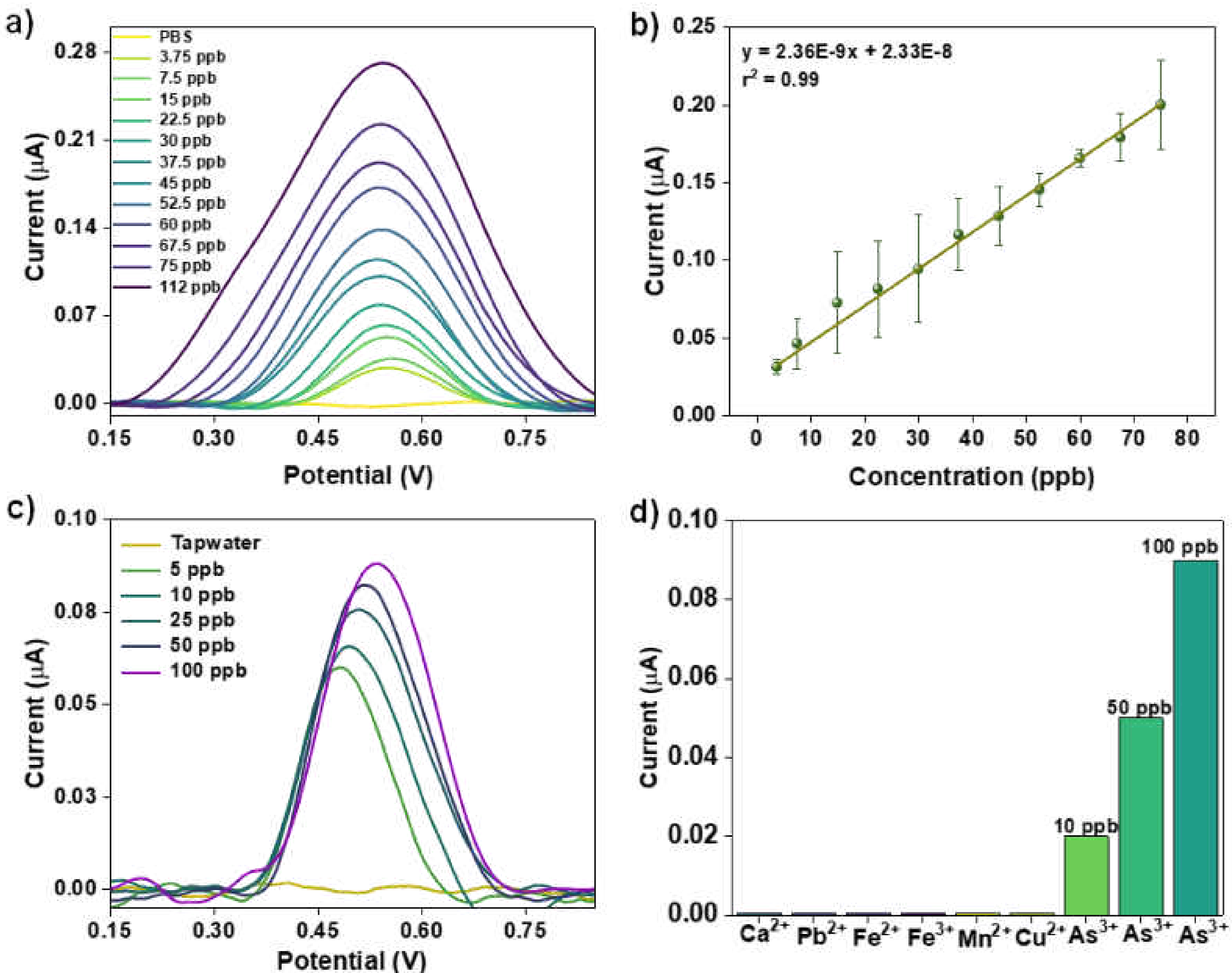


1,2-bis(diphenylphosphino)ethane (DPPE)

Electrospray deposition

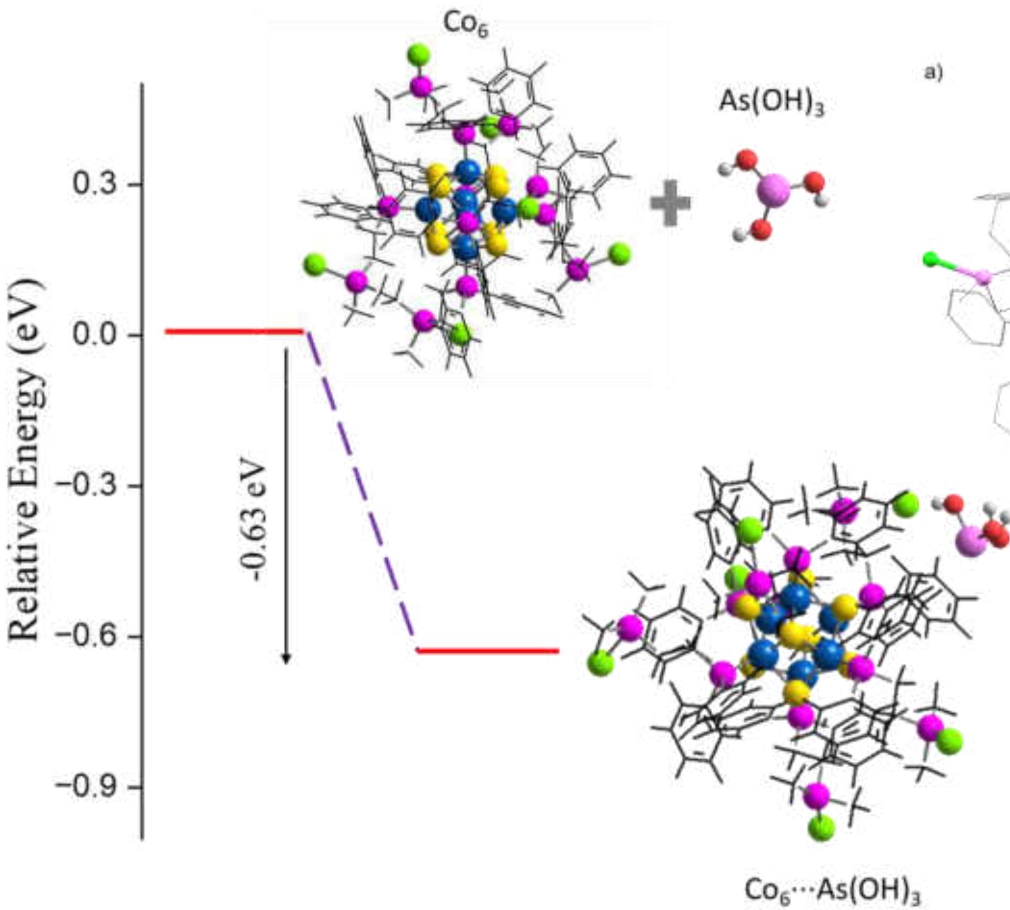


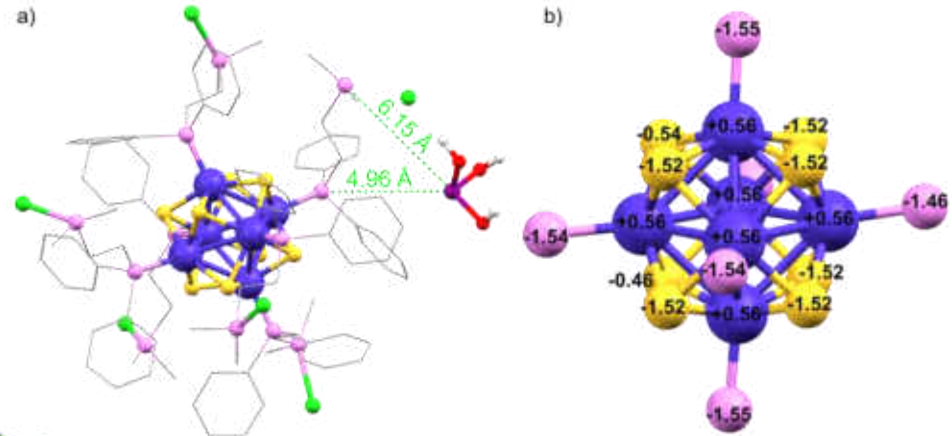
Sensing



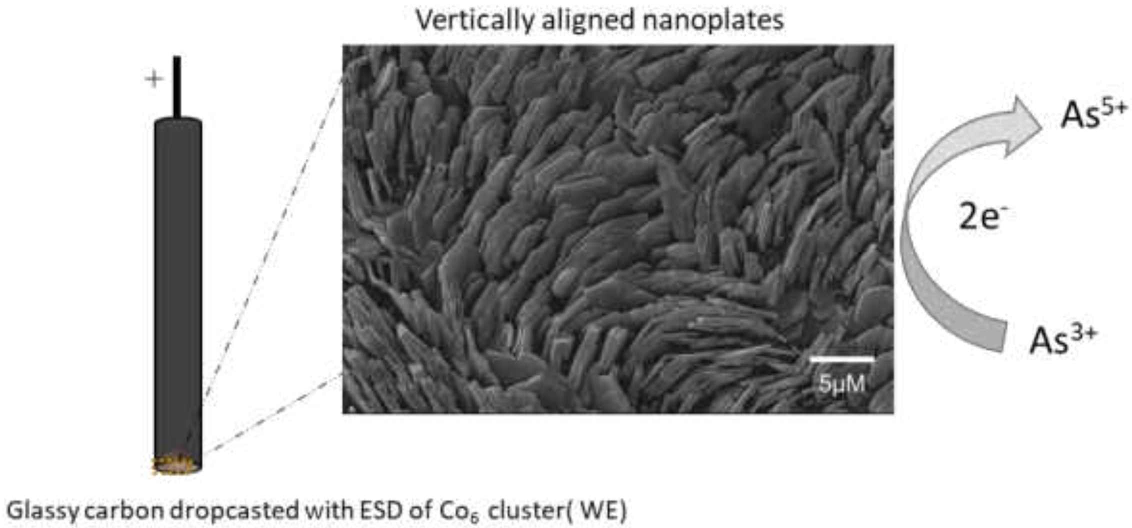
a)
PBS
3.75 ppb
7.5 ppb
15 ppb
22.5 ppb
30 ppb
37.5 ppb
45 ppb
52.5 ppb
60 ppb
67.5 ppb
75 ppb
112 ppb
Current (μA)
Potential (V)
b)
y = 2.36E-9x + 2.33E-8
r² = 0.99
Current (μA)
Concentration (ppb)
c)
Tapwater
5 ppb
10 ppb
25 ppb
50 ppb
100 ppb
Current (μA)
Potential (V)
d)
100 ppb
50 ppb
10 ppb
Current (μA)
Ca²⁺ Pb²⁺ Fe²⁺ Fe³⁺ Mn²⁺ Cu²⁺ As³⁺ As³⁺ As³⁺

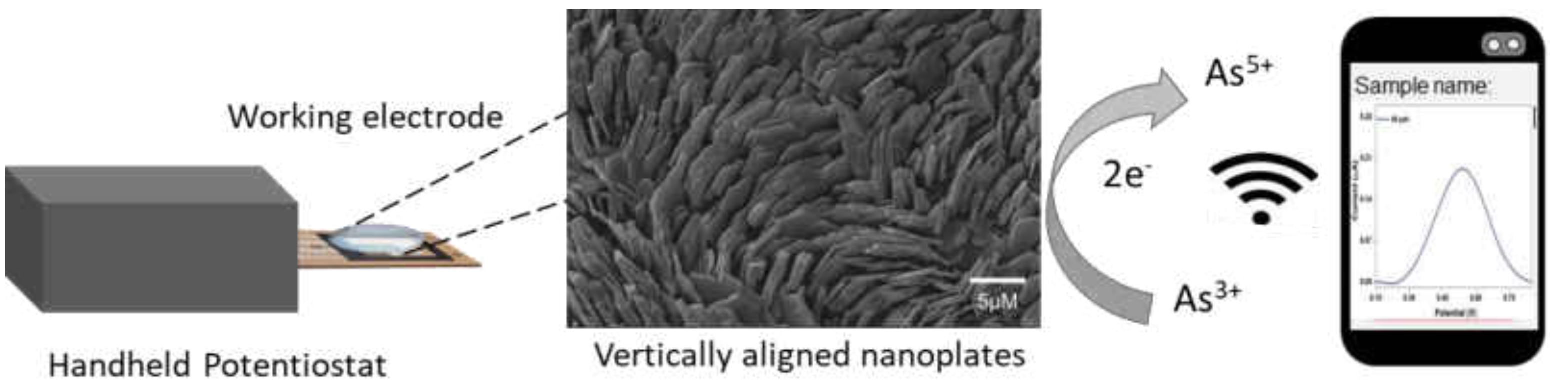
Computational insights





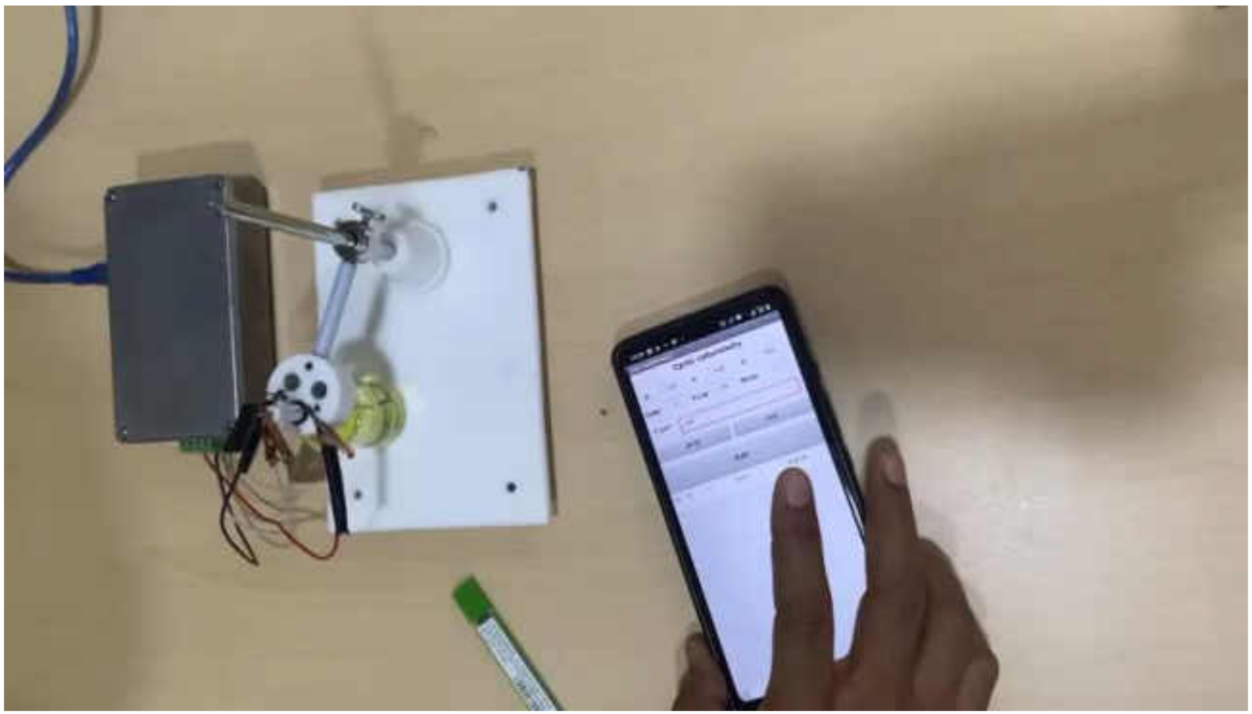
Working electrode





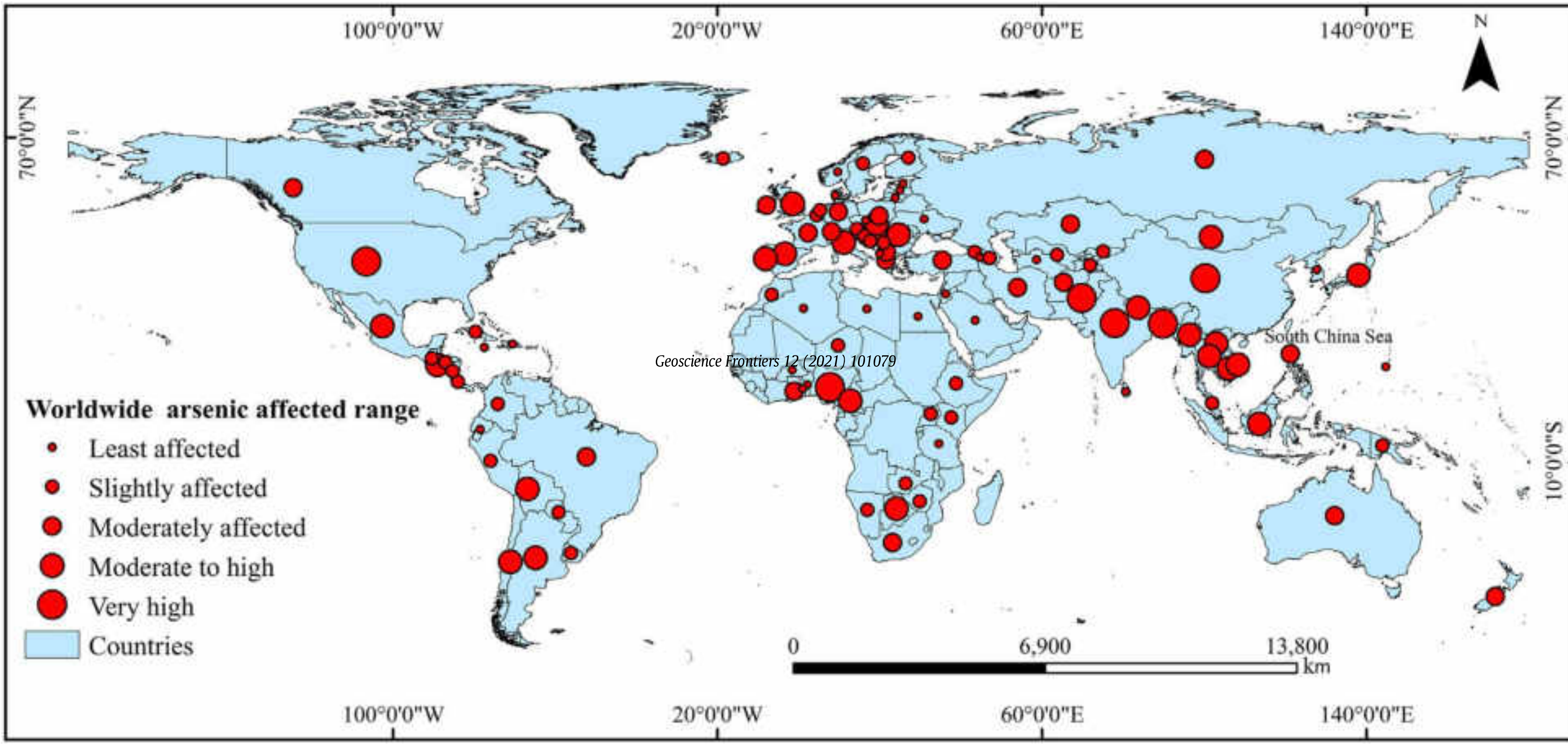
Anagha Jose et al. 2023

Analytical devices



Sourav Kanti Jana

Arsenic poisoning across the world



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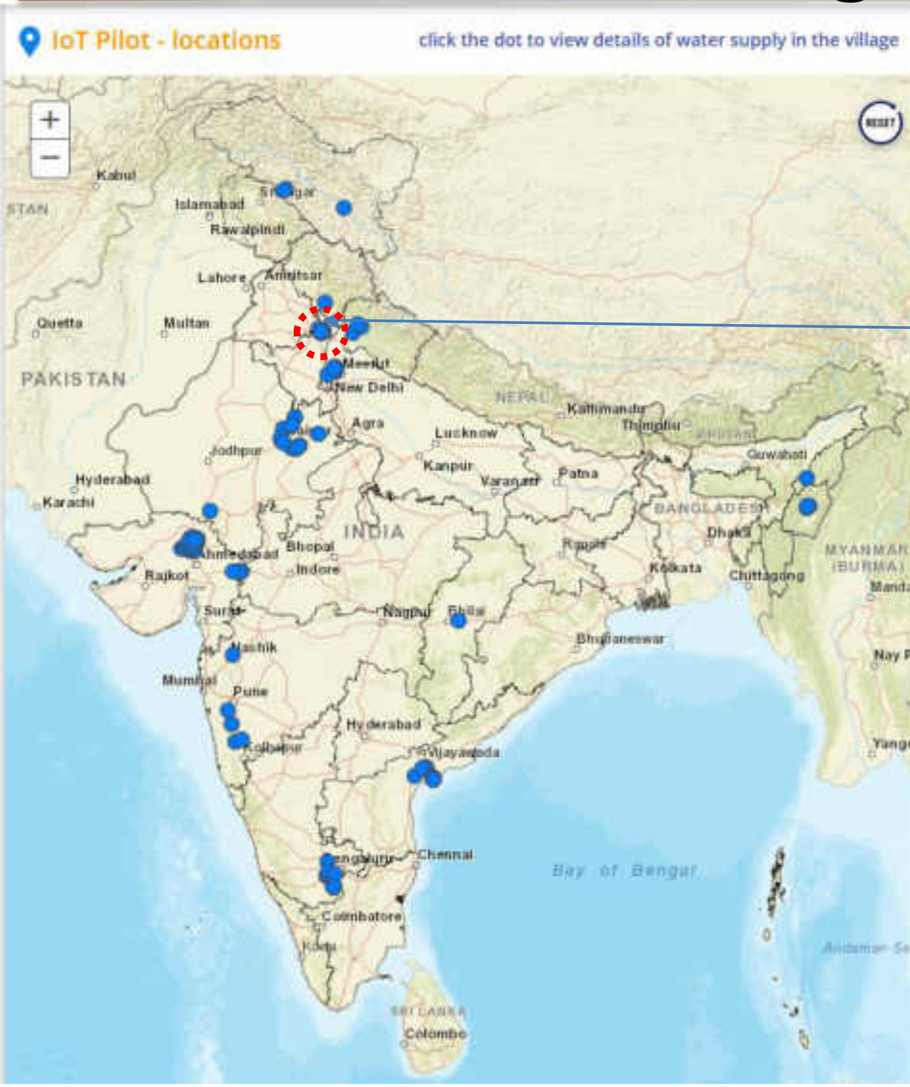
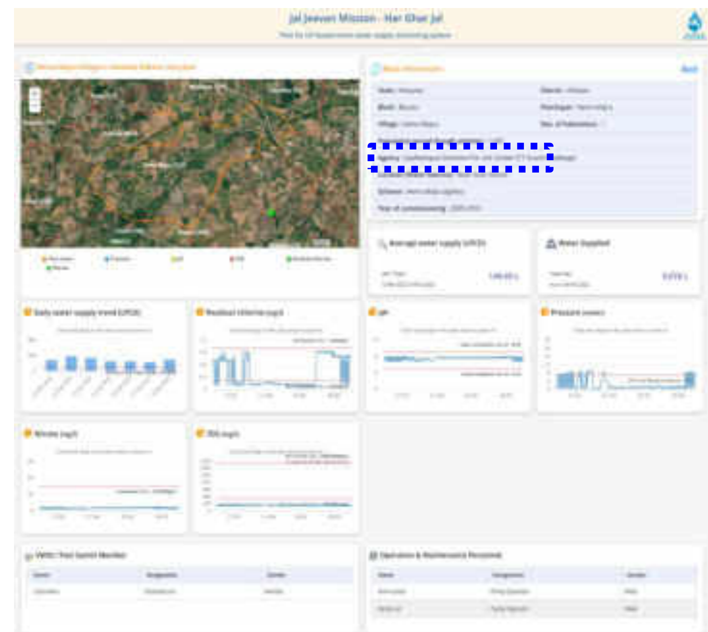
India's water is being monitored

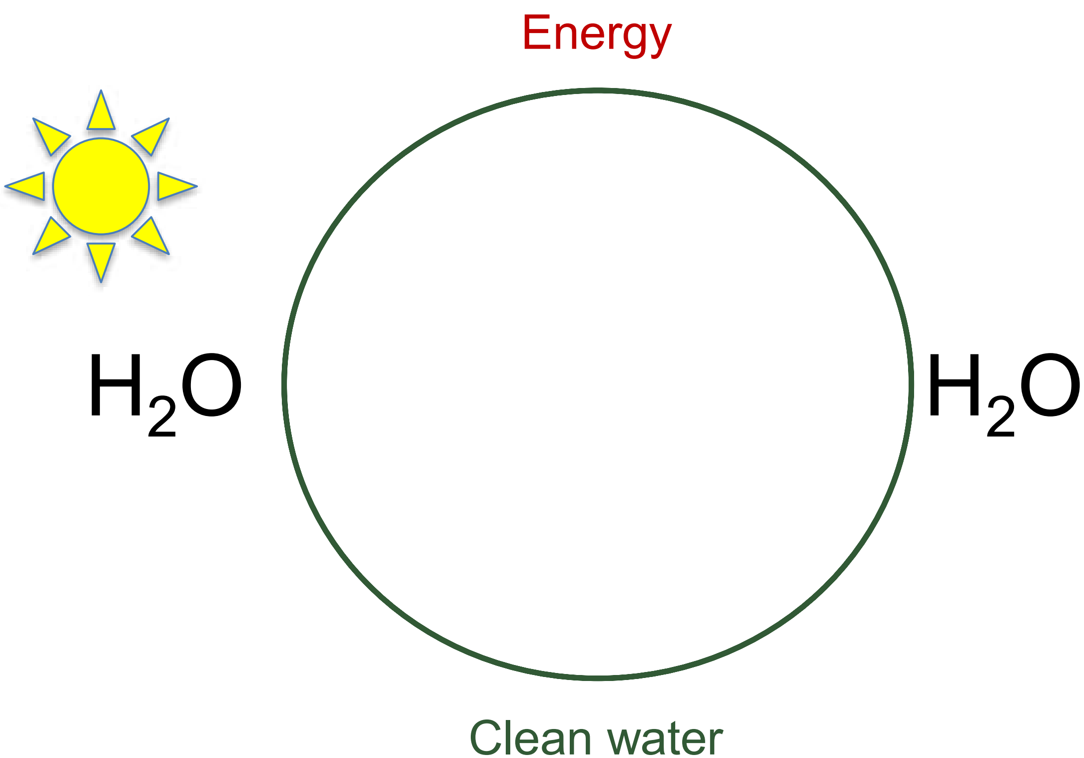


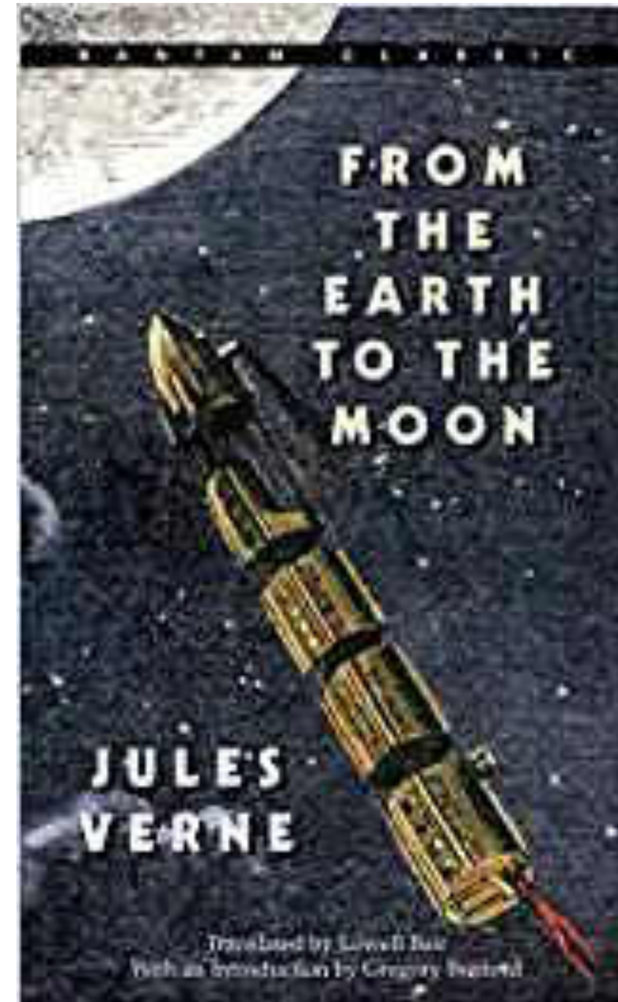
IITM/IISc

Installations made by four companies



Our dreams become reality with materials





Affordable, inclusive, sustainable and contextual excellence

International Centre for Clean Water

The AMRIT Team, 2013

Water team at IIT: A. Sreekumaran Nair, Anshup, M. Udhaya Sankar, Amrita Chaudhary, Renjis T. Tom, T. S. Sreeprasad, Udayabhaskararao Thumu, M. S. Bootharaju, K. R. Krishnadas, Kalamesh Chaudhari, Soujit Sengupta, Depanjan Sarkar, Avijit Baidya, Swathy Jakka Ravindran, Abhijit Nag, S. Vidhya, Biswajit Mondal, Krishnan Swaminathan, Azhardin Gnayee, Sudhakar Chennu, A. Suganya, Rabiul Islam, Sritama Mukherjee, Tanvi Gupte, Jenifer Shantha Kumar, A. Anil Kumar, Ankit Nagar, Ramesh Kumar Soni, Tanmayaa Nayak, Sonali Seth, Shihabudheen M. Maliyekkal, G. Velmurugan, Wakeel Ahmed Dar, Ganapati Natarajan, N. Pugazhenthiran, A. Leelavathi, Sahaja Aigal, S.Gayathri, Bibhuti Bhusan Rath, Ananthu Mahendranath, Harsh Dave, Erik Mobegi, Egor Moses, Hemanta R. Naik, Sourav Kanti Jana,...

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

Funding: Department of Science and Technology, Government of India

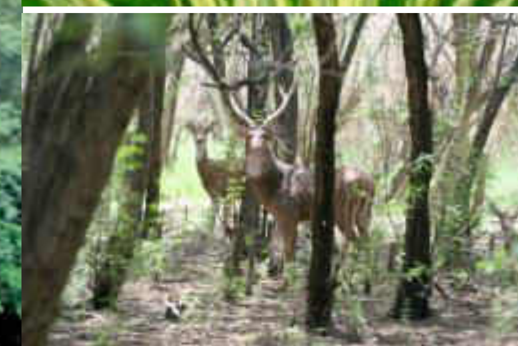
Start-ups and partners:

PhD Theses: Bindhu Varughese, M. R. Resmi, M. Venkataramanan, N. Sandhyarani, R. Selvan, A. Sreekumaran Nair, M. J. Rosemary, Renjis T. Tom, C. Subramaniam, Jobin Cyriac, V. R. Rajeev Kumar, D. M. David Jeba Singh, Akshaya Kumar Samal, E. S. Shibu, M. A. Habeeb Muhammed, P. R. Sajanlal, T. S. Sreeprasad, J. Purushothaman, T. Udayabhaskararao, M. S. Bootharaju, Soumabha Bag, Robin John, Kamalesh Chaudhari, Ammu Mathew, Indranath Chakraborty, Radha Gobinda Bhuin, Ananya Baksi, Amitava Srimony, Anirban Som, Rabin Rajan Methikkalam, K. R. Krishnadas, Soujit Sengupta, Depanjan Sarkar, Atanu Ghosh, Rahul Narayanan, Avijit Baidya, Shridevi Bhat, Papri Chakraborty, Swathy Jakka Ravindran, C. K. Manju, Abhijit Nag, S. Vidhya, Jyoti Sarita Mohanty, Debasmita Ghosh, Jyotirmoy Ghosh, Md. Bodiuzzaman, Biswajit Mondal, Tripti Ahuja, Esma Khatun, Krishnan Swaminathan, K. S. Sugi, Amrita Chakraborty, Sudhakar Chennu, Sritama Mukherjee, Madhuri Jash, Sandeep Bose, Md. Rabiul Islam, Pallab Basuri, Mohd Azhardin Ganayee, Tanvi Gupte

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


IIT Madras Research Park

Indian Institute of Technology Madras



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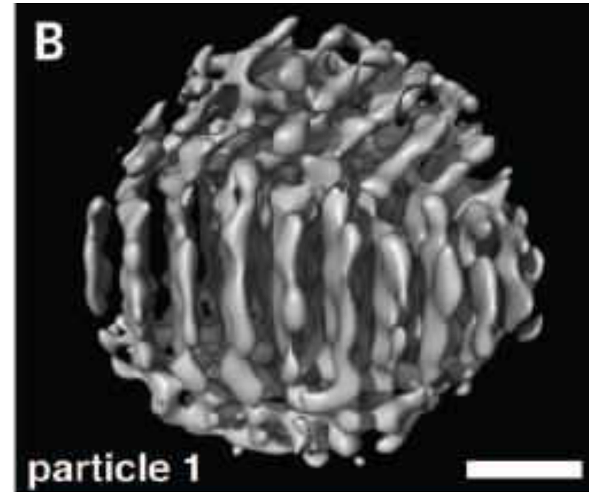
Thank you all

Seeing atoms, molecules and assemblies



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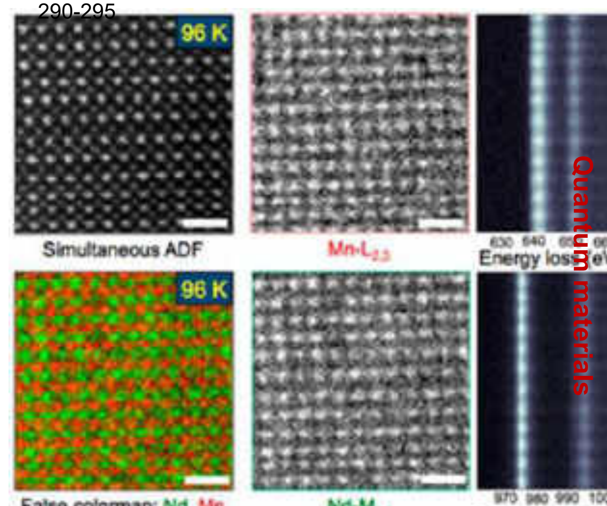

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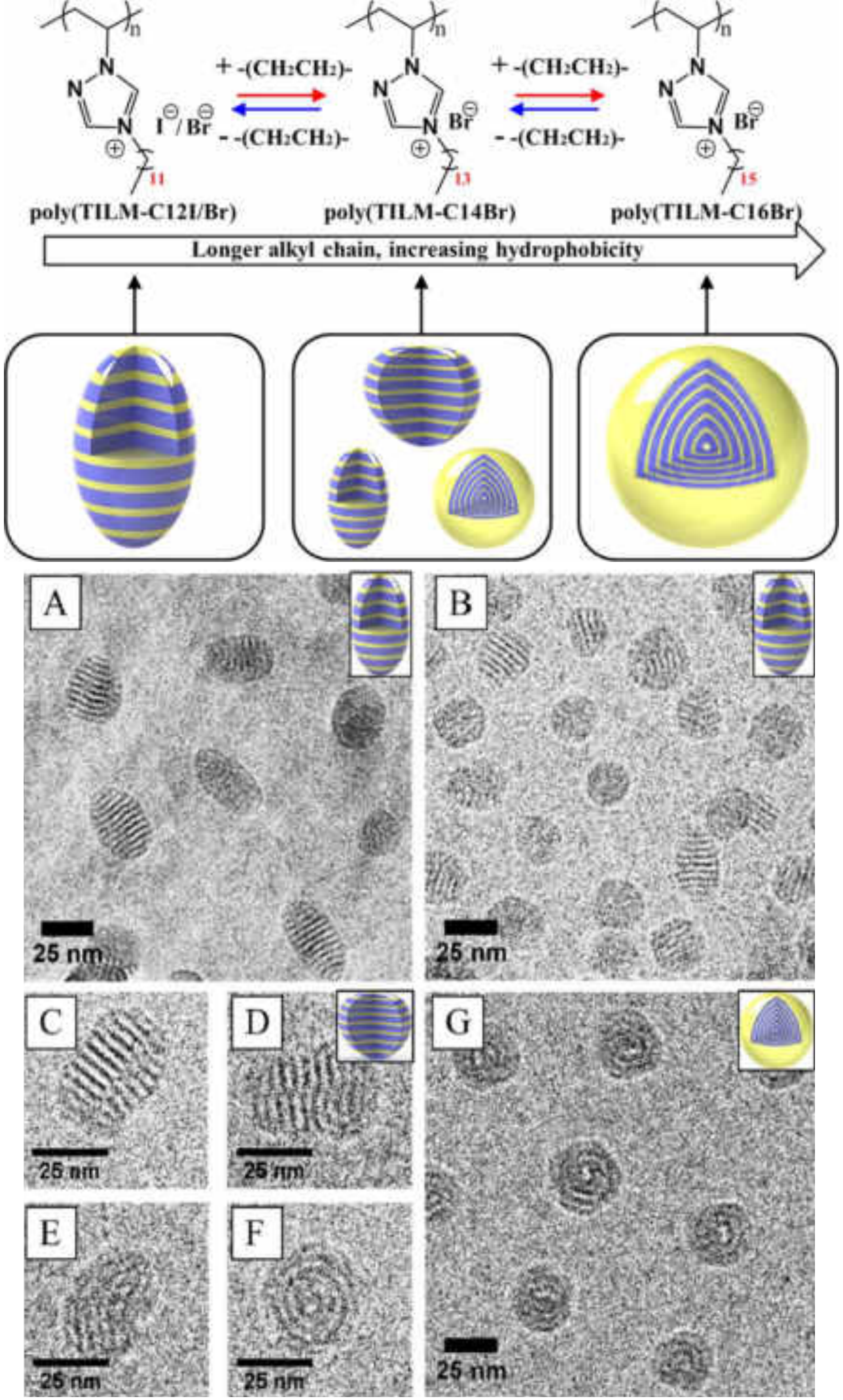
Nature and evolution of incommensurate charge order in manganites visualized with cryogenic scanning transmission electron microscopy. Baggari, I. E. et al., *Proc. Natl. Acad. Sci*. **2018**, *115*, 1445−1450.



Morphological variations from “wasp-like” to “spaghetti ball”/“onion-like” configurations influenced by the different alkyl chain lengths

Overcome the limitations of precise control over structural complexity and ordering in polymer nanoparticles

Cryo-EM images of PIL nanoparticles (A) 4-n-dodecyl-1-vinyl-1,2,4-triazolium iodide (TILM-C12I), (B) 4-n-dodecyl-1-vinyl-1,2,4-triazolium bromide (TILM-C12Br), and its longer alkyl chain derivatives, (C-F) TILM-C14Br and (G) TILM-C16Br.

Weiyi Zhang et al., Internal Morphology-Controllable Self-Assembly in Poly(Ionic Liquid) Nanoparticles. ACS Nano 2016, 10 (8), 7731–7737.https://doi.org/10.1021/acsnano.6b03135.