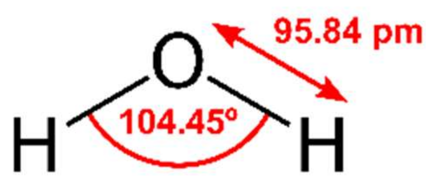
Since 1959



Affordable clean water using advanced materials

T. 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.

Associate Editor

ACS Sustainable Chemistry & Engineering

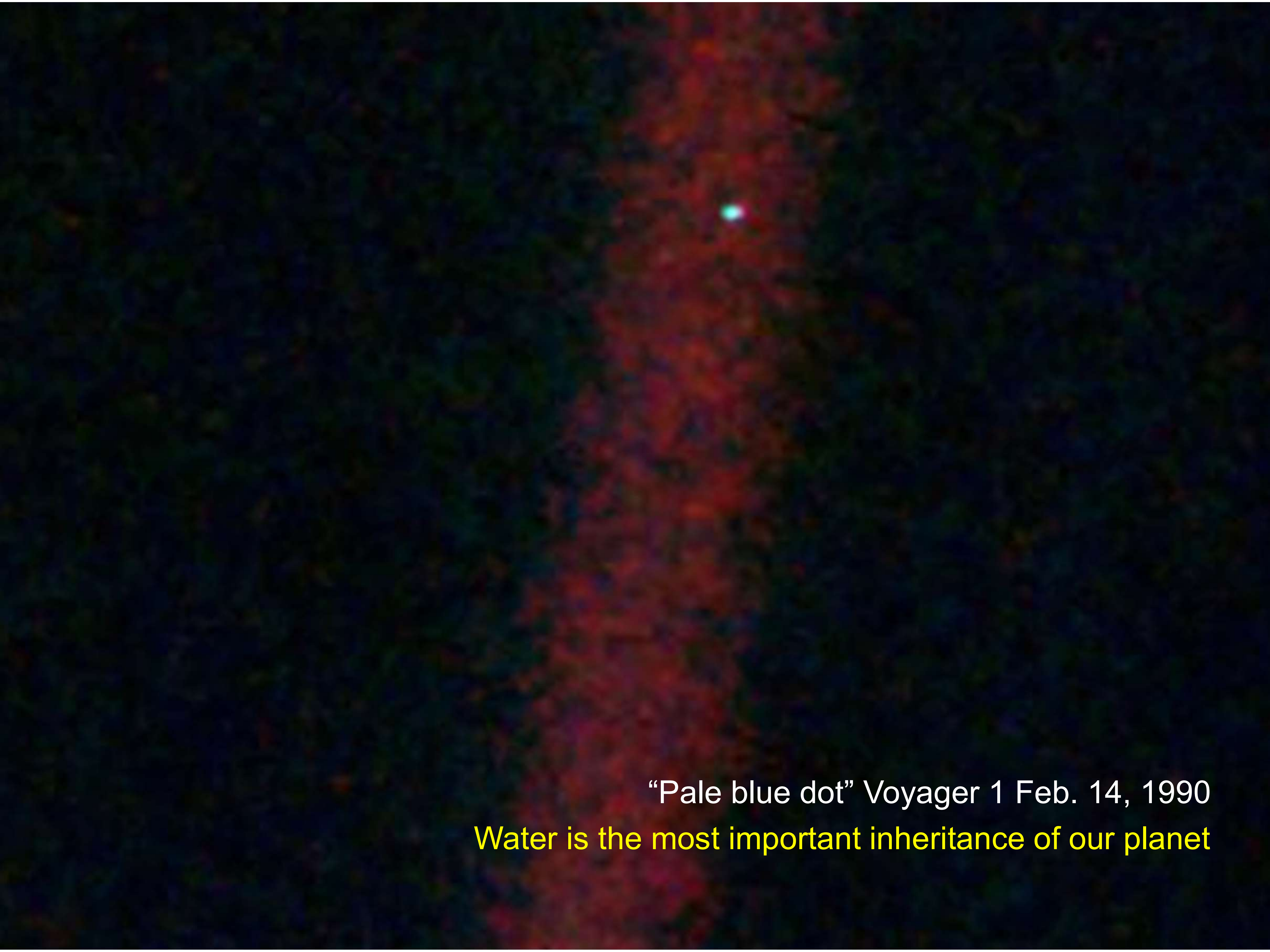
Deeksha Gupta, Kunal Gupta, Aparna Sharma

All my colleagues at ACS India

Professor-in-charge

International Centre for Clean Water

No. 1 April 9, 2020



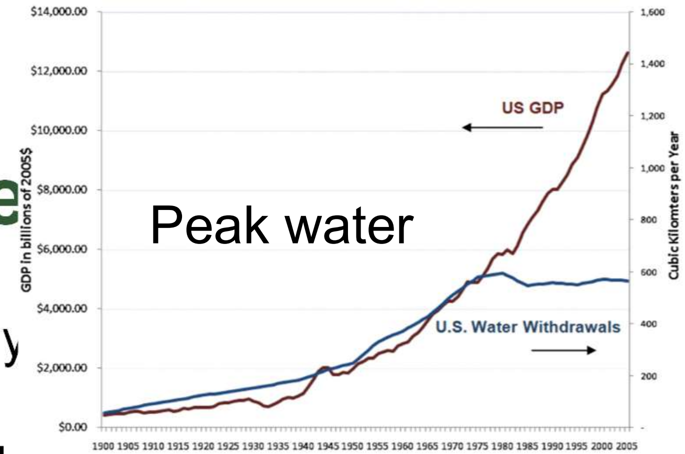
“Pale blue dot” Voyager 1 Feb. 14, 1990

Water is the most important inheritance of our planet

Water is at the entre of action

There is water in everything we do.

Water is big…. **Are we safe**



Peter H. Gleick and Meena Palaniappan, PNAS, 2010, 107, 11155–11162

Per capita water availability – 1500 CM per y

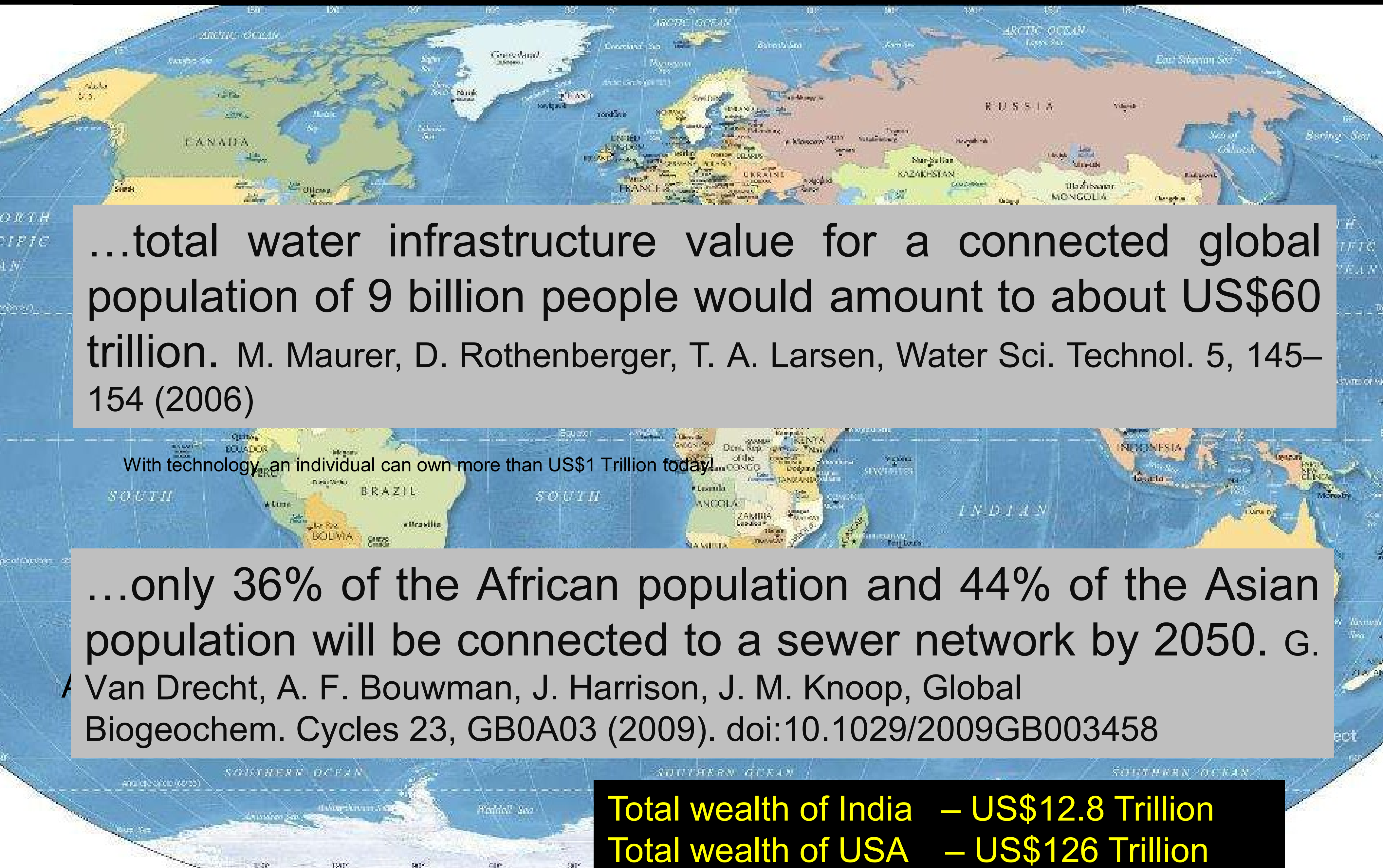
That water and its benefits need to reach all.

3Ss for water **Store – Sensitive – Smart**

Average annual rainfall 1085 mm, 85th in a list of 186 countries
Traditions of storage and conservation – we store just about 8%
Water is for all – for every living form
83% of freshwater species have declined globally in the last 50 years!
GDP can grow even by capping freshwater withdrawals
We must find technologies of relevance
Energy - food – clothing – construction – manufacturing - …..

Water is big in every scale –
Gaps, opportunities, wealth, satisfaction

Water, sanitation and inequality



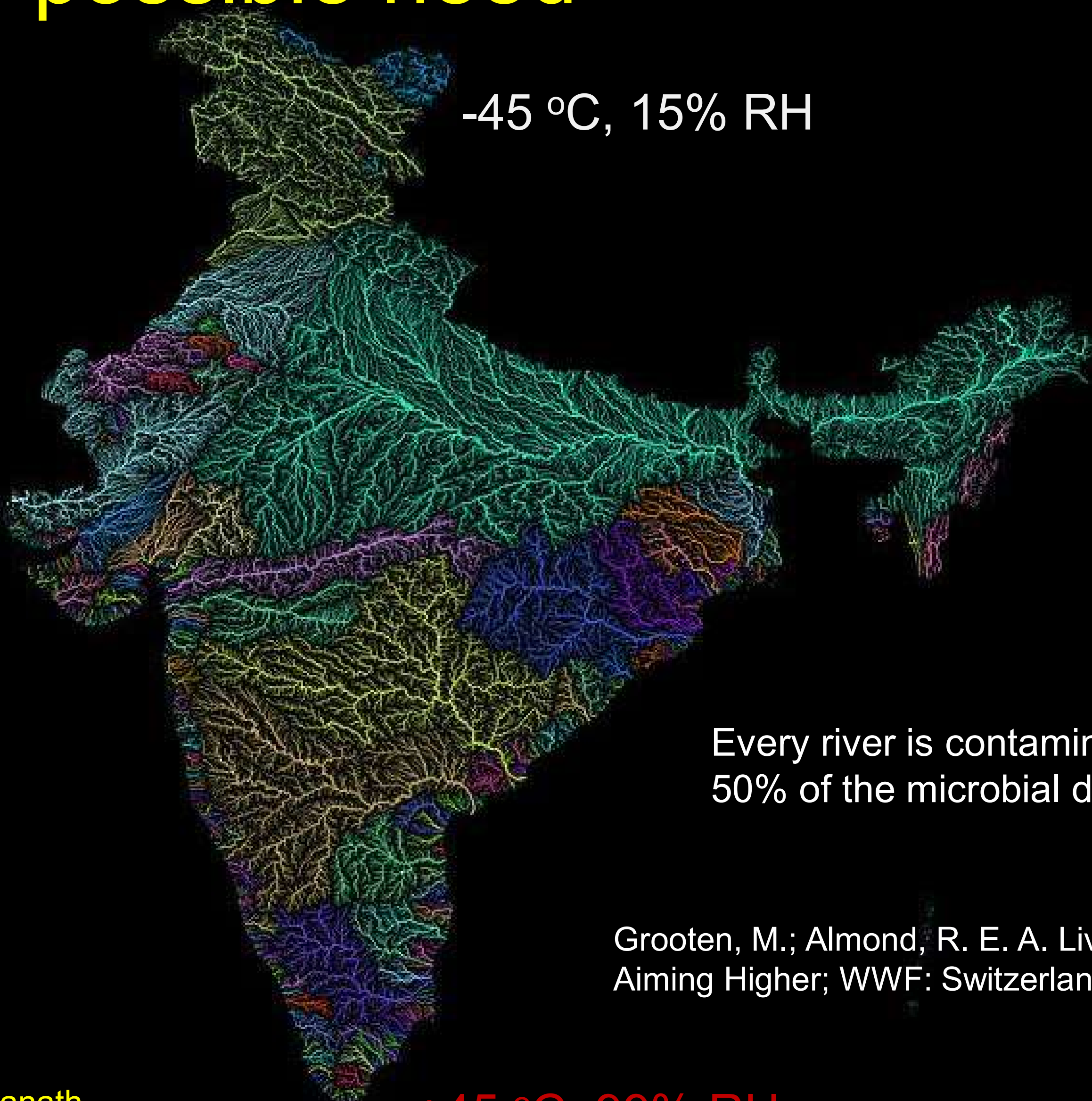
…total water infrastructure value for a connected global population of 9 billion people would amount to about US$60 trillion. M. Maurer, D. Rothenberger, T. A. Larsen, Water Sci. Technol. 5, 145–154 (2006)

With technology, an individual can own more than US$1 Trillion today!

…only 36% of the African population and 44% of the Asian population will be connected to a sewer network by 2050. G. Van Drecht, A. F. Bouwman, J. Harrison, J. M. Knoop, Global Biogeochem. Cycles 23, GB0A03 (2009). doi:10.1029/2009GB003458

Total wealth of India – US$12.8 Trillion
Total wealth of USA – US$126 Trillion

Challenges
Every possible need



-45 ^{o}C, 15% RH

Arsenic
Fluoride
Uranium
Mercury
Chromium
Perchlorate
Nitrate
Pesticides
Antibiotics
Plastics
Detergents
…..

Every river is contaminated
50% of the microbial diversity is lost for ever

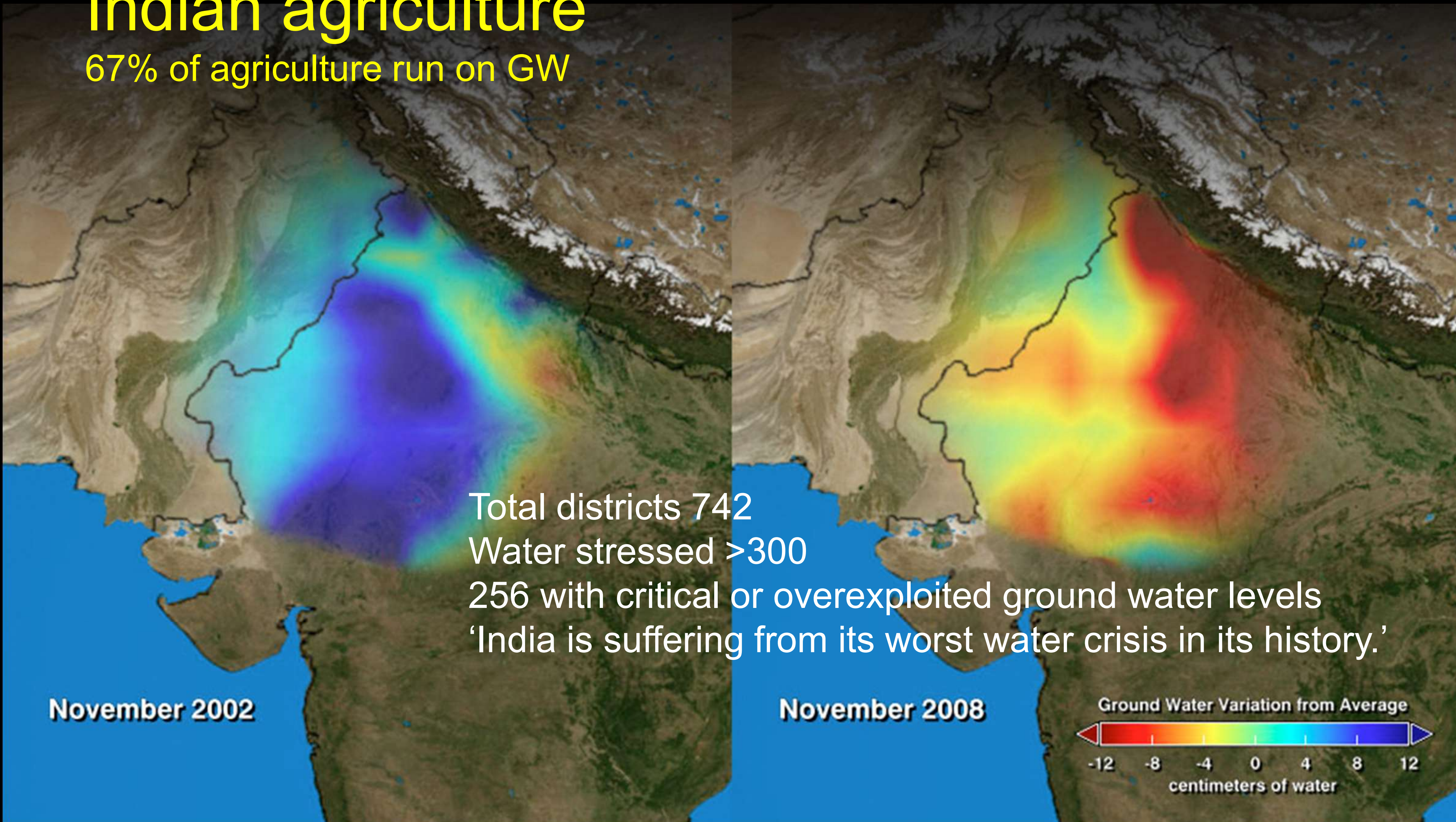
Grooten, M.; Almond, R. E. A. Living Planet Report - 2018: Aiming Higher; WWF: Switzerland, 2018.

From S. Vishwanath

+45 ^{o}C, 99% RH

Indian agriculture

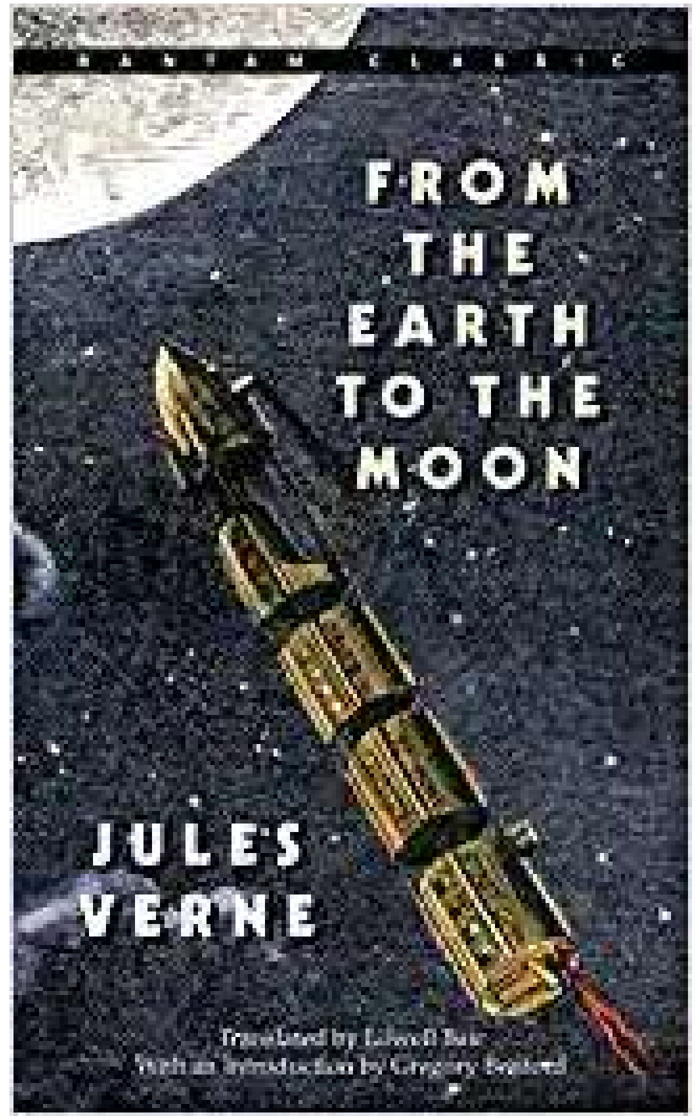
67% of agriculture run on GW



Total districts 742
Water stressed >300
256 with critical or overexploited ground water levels
‘India is suffering from its worst water crisis in its history.’

Data from NASA

Our dreams become reality with materials



Water purification, history

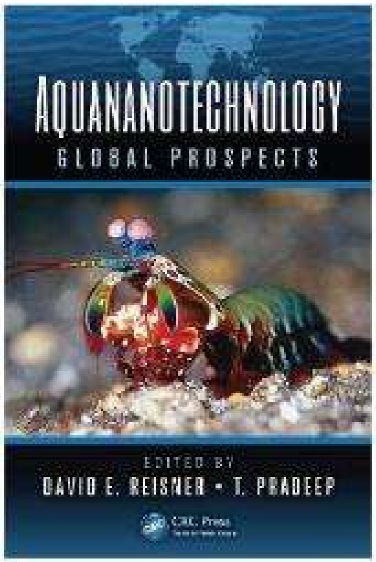
Important milestones in the history of water purification (1800–2007) from the perspective of noble metal nanoparticles in water treatment (compiled from multiple sources on the World Wide Web).

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)

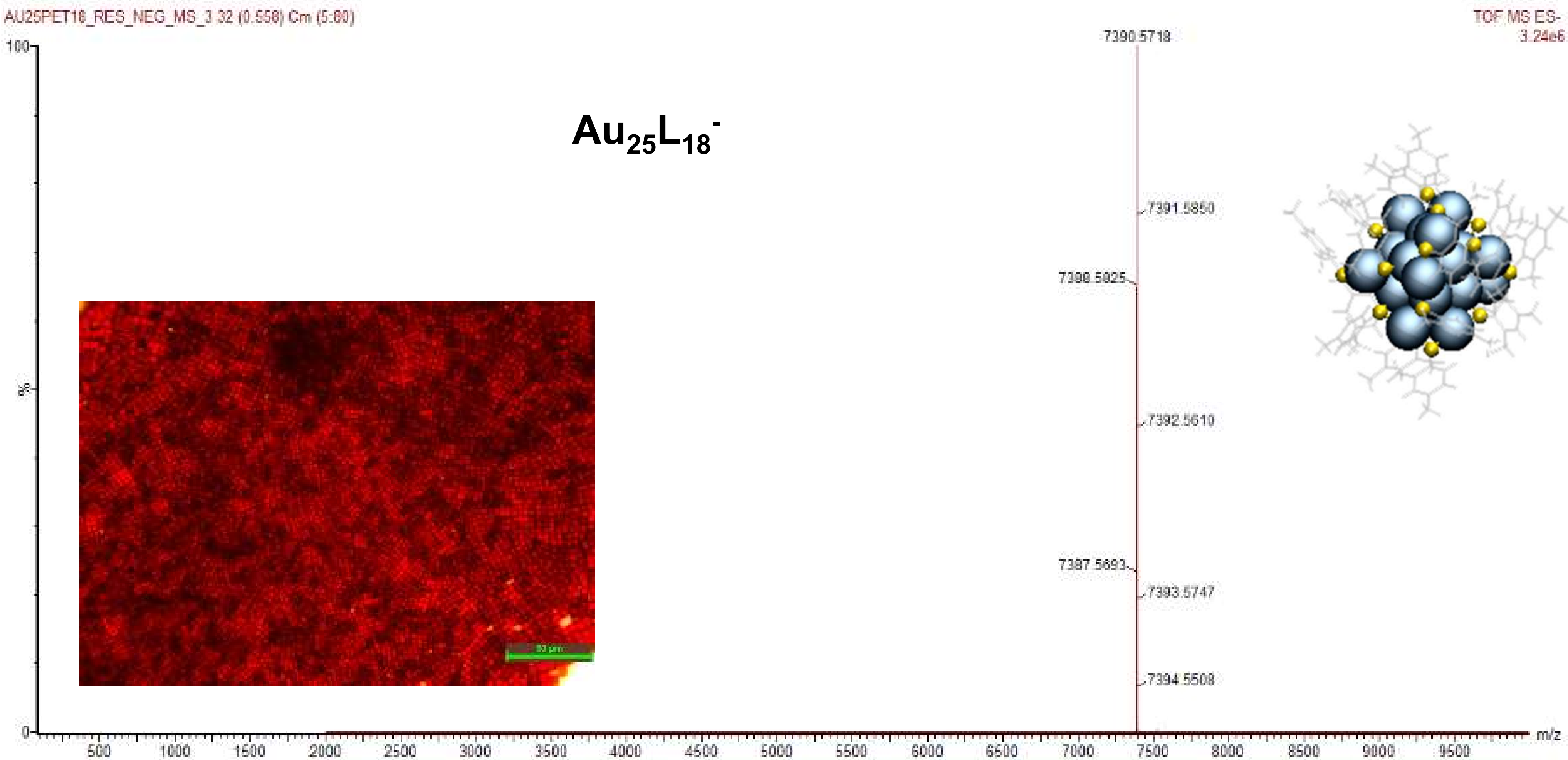
T. Pradeep and Anshup, *Thin Solid Films*, 2009

Affordable clean water is a problem of advanced materials

New adsorbents
New sensors
New catalysts
Novel phenomena
New devices



Nanomaterials are now atomically precise



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

Nanomaterials can solve real problems

ACS Sustainable Chemistry & Engineering Editorial, December 2016

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

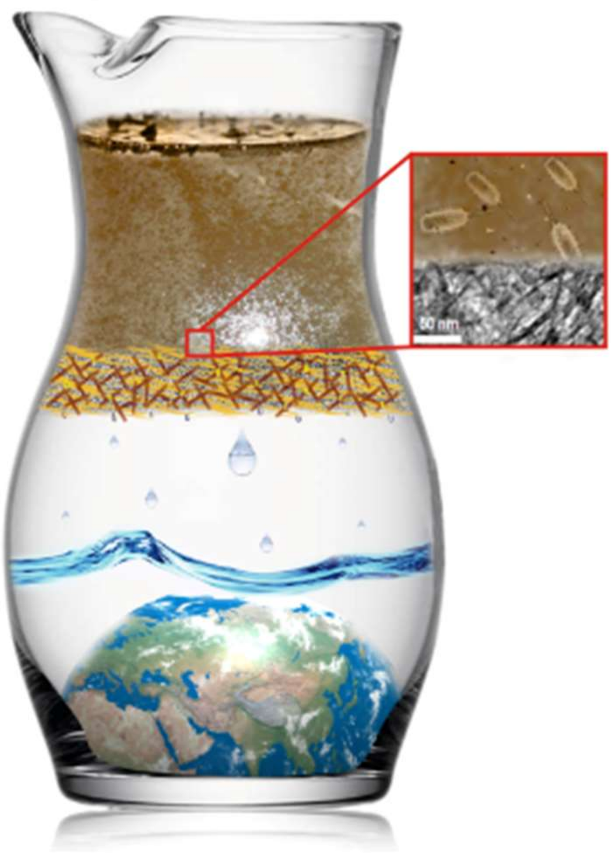
Mohan Udhaya Sankar[1], Sahaja Aigal[1], Shihabudheen M. Maliyekkal[1], Amrita Chaudhary, Anshup, Avula Anil Kumar, Kamalesh Chaudhari, and Thalappil Pradeep[2]

Unit of Nanoscience and Thematic Unit of Excellence, Department of Chemistry, Indian Institute of Technology Madras, Chennai 600 036, India

Edited by Eric Hoek, University of California, Los Angeles, CA and accepted by the Editorial Board April 4, 2013 (received for review November 21, 2012)

Creation of affordable materials for constant release of silver ions in water is one of the most promising ways to provide microbially safe drinking water for all. Combining the capacity of diverse nano-composites to other contami affordable, all- without electr synthesis of st uously in the drinking wate surfaces. Here be synthesized out the use of sand-like prope forms. These m water purifier ily. The ability ambient temp water purifica

hybrid | green |

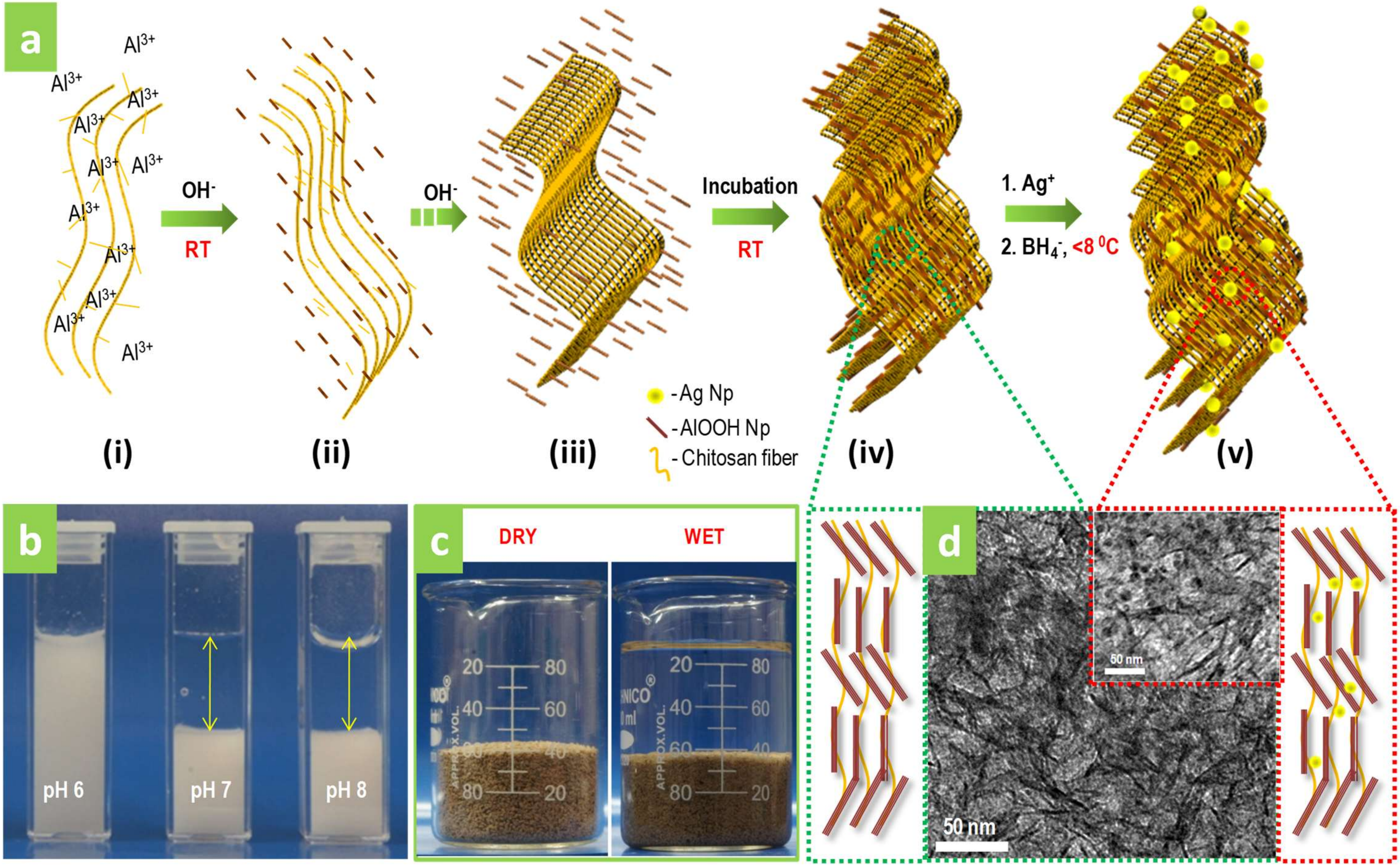


release into water are not available; and (*c*) continued retention of the nanoparticles in the matrix is difficult.

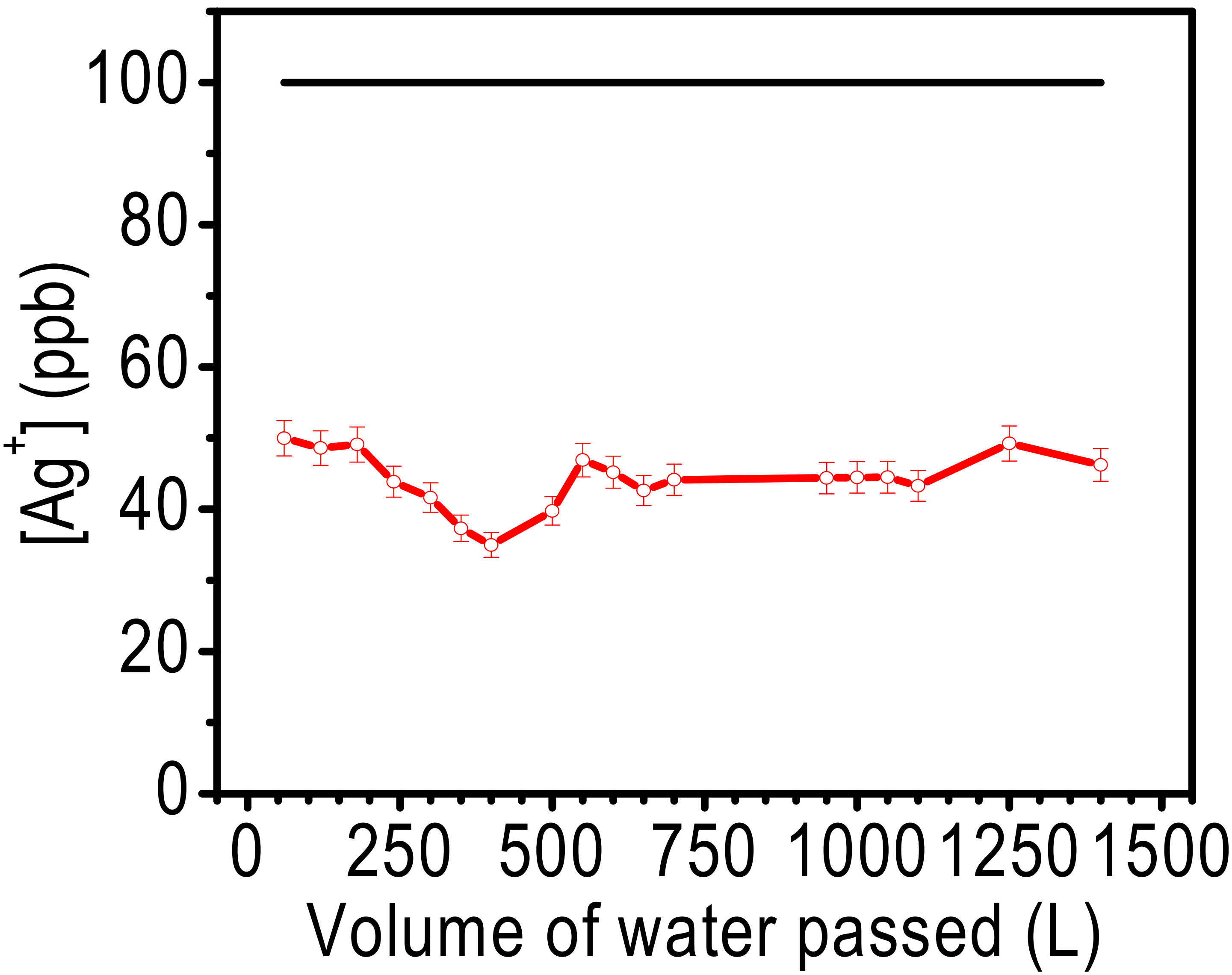
In this work, we demonstrate a unique family of nanocrystalline tal oxyhydroxide-chitosan granular composite materials pre-ed at near room temperature through an aqueous route. The in of crystallinity in the composition is attributed to abundant -O- l -OH functional groups on chitosan, which help in the crys-ization of metal oxyhydroxide and also ensure strong covalent ding of the nanoparticle surface to the matrix. X-ray photo-ctron spectroscopy (XPS) confirms that the composition is rich h surface hydroxyl groups. Using hyperspectral imaging, the ence of nanoparticle leaching in the water was confirmed. ther, a unique scheme to reactivate the silver nanoparticle face is used for continual antimicrobial activity in drinking ers. Several other composites have been developed that can venge other contaminants in water. We demonstrate an af-dable water purification device based on such composites de-oped over several years and undergoing field trials in India, as otential solution for widespread eradication of the waterborne ease burden.

ults and Discussion

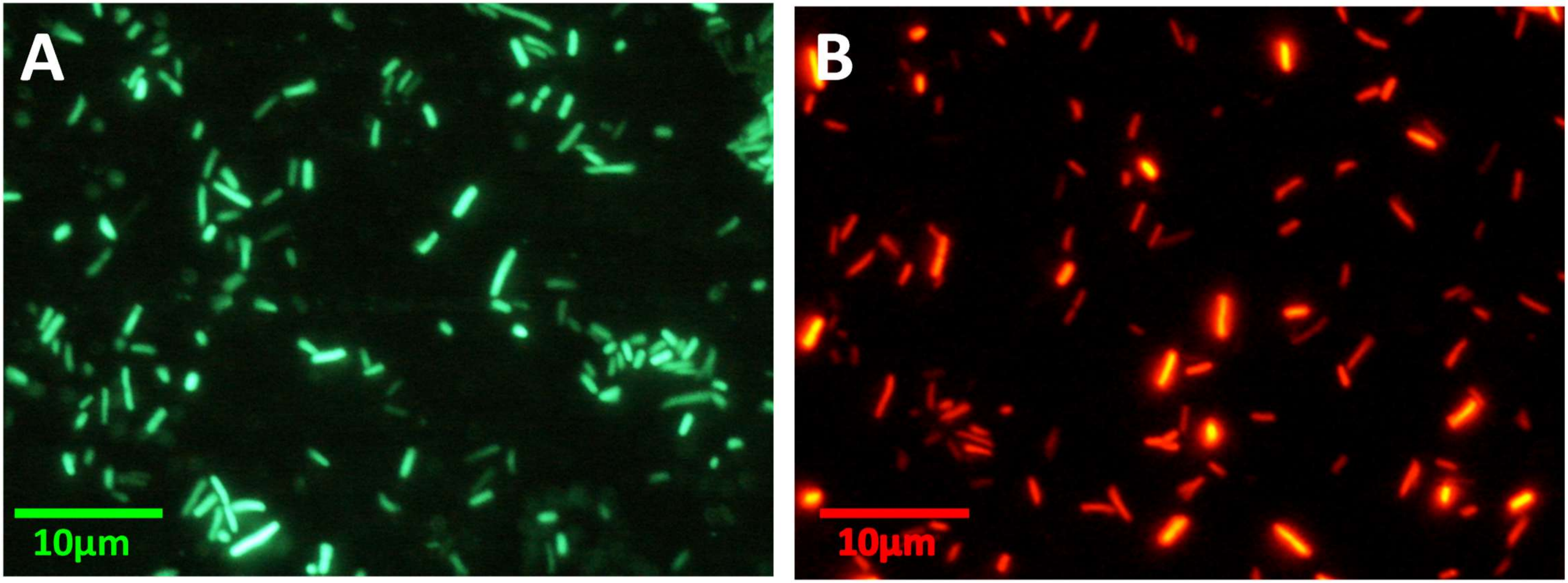
New materials

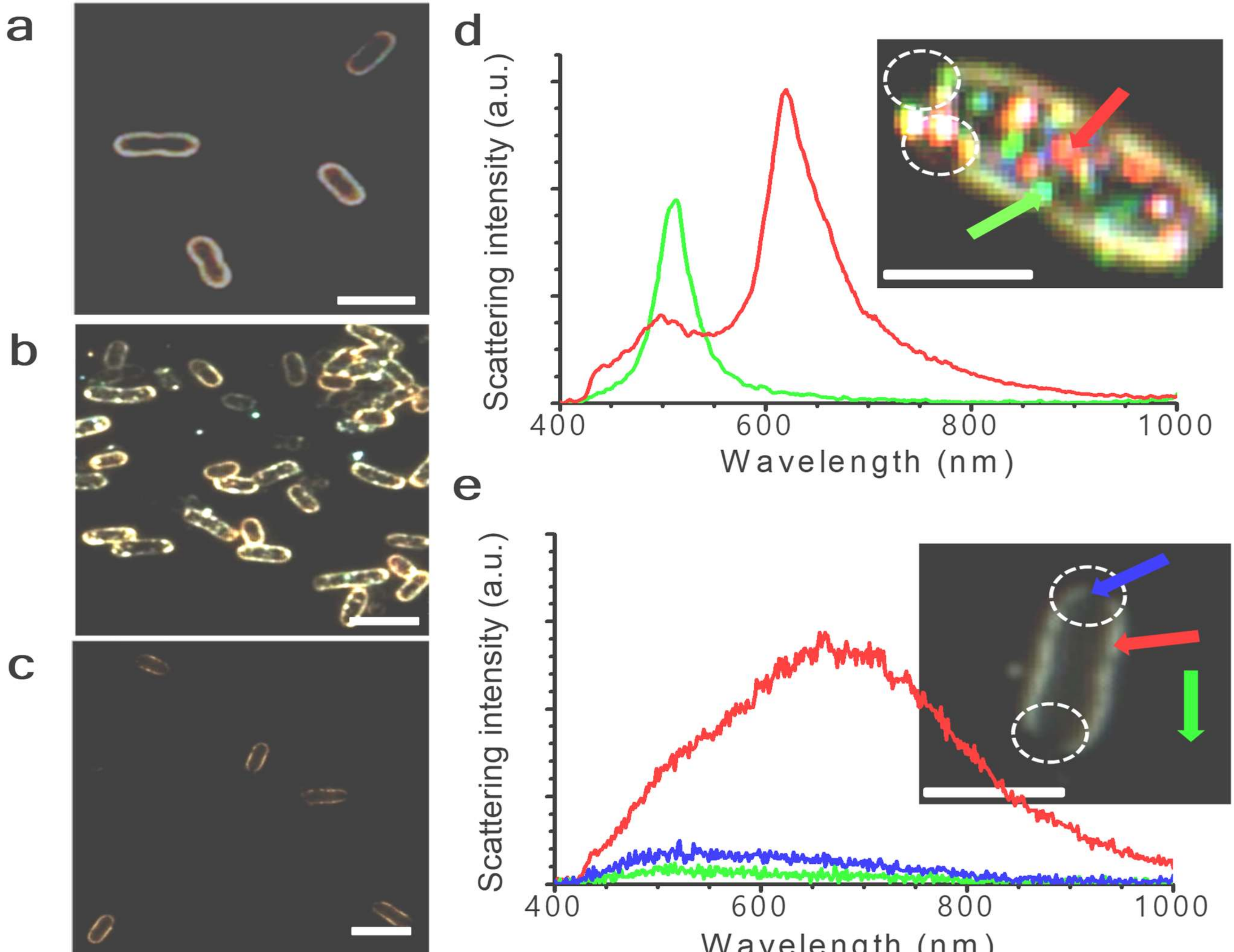


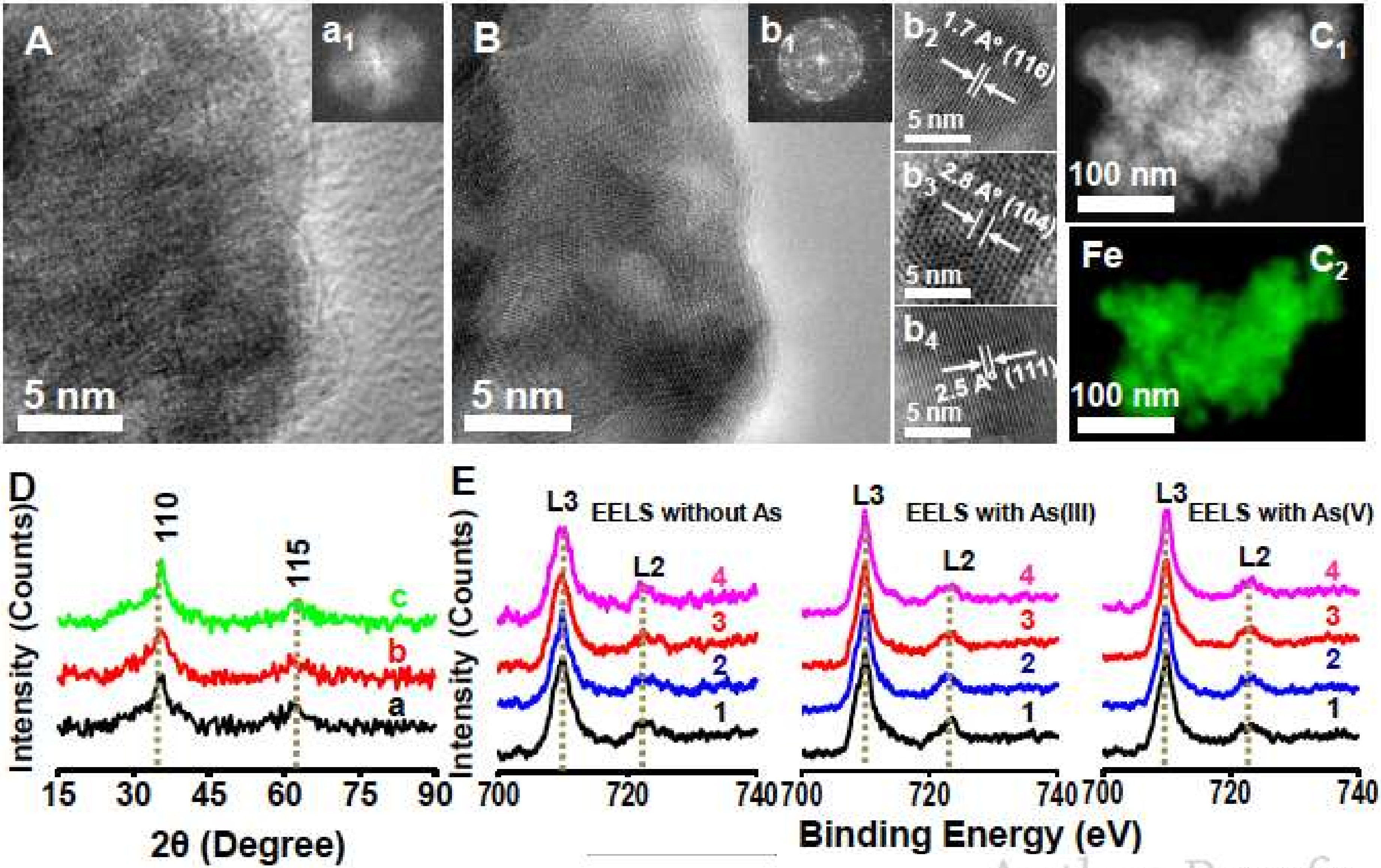
What is special?

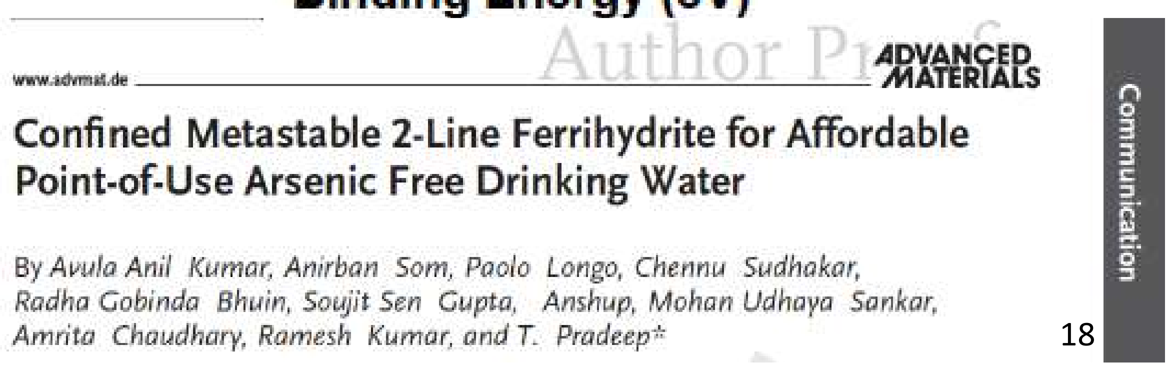


Live/dead staining experiments




a
b
c
d
Scattering intensity (a.u.)
400
600
800
1000
Wavelength (nm)
e
Scattering intensity (a.u.)
400
600
800
1000
Wavelength (nm)




Author Proof

ADVANCED MATERIALS

www.advmat.de

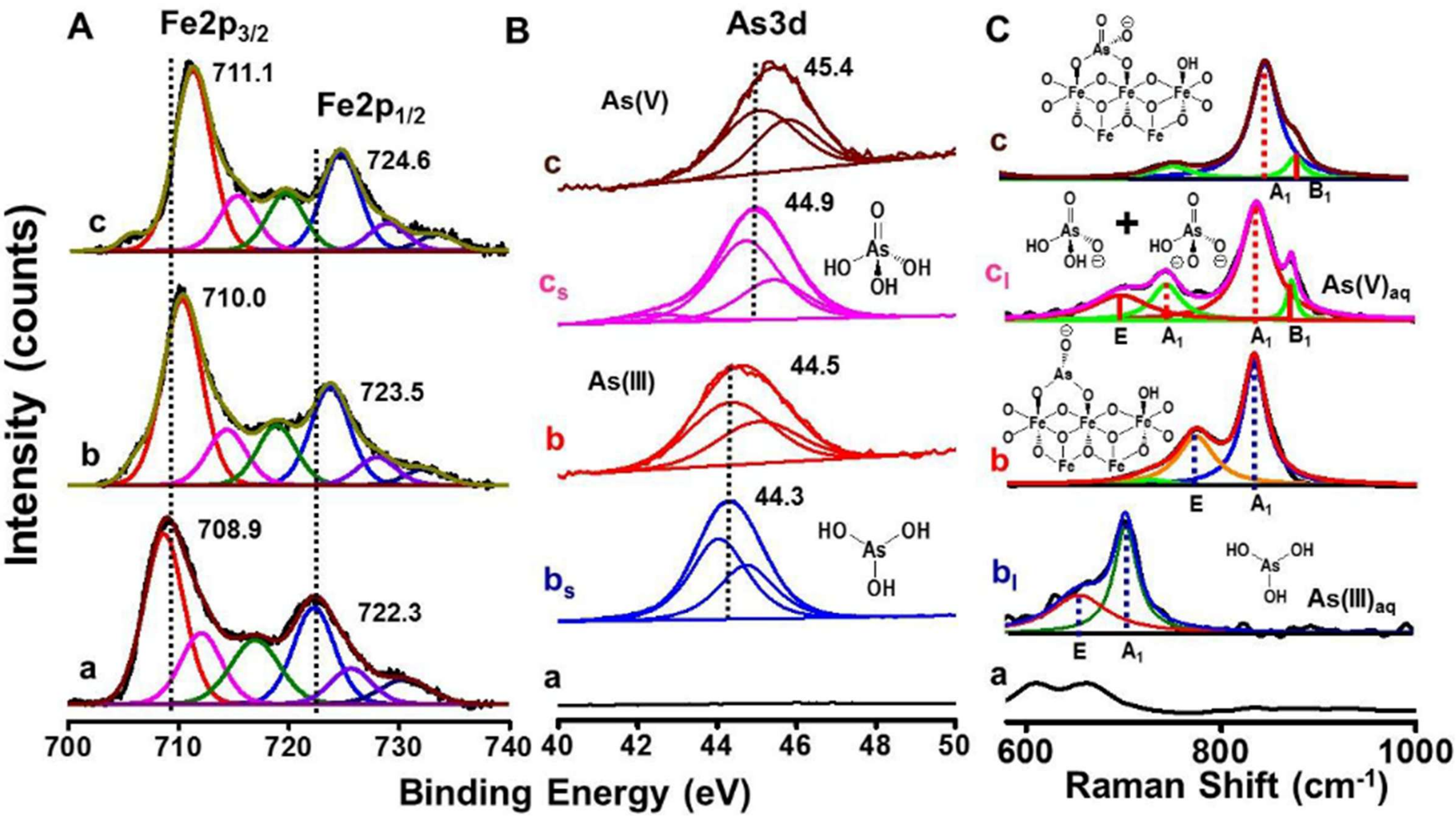
Communication

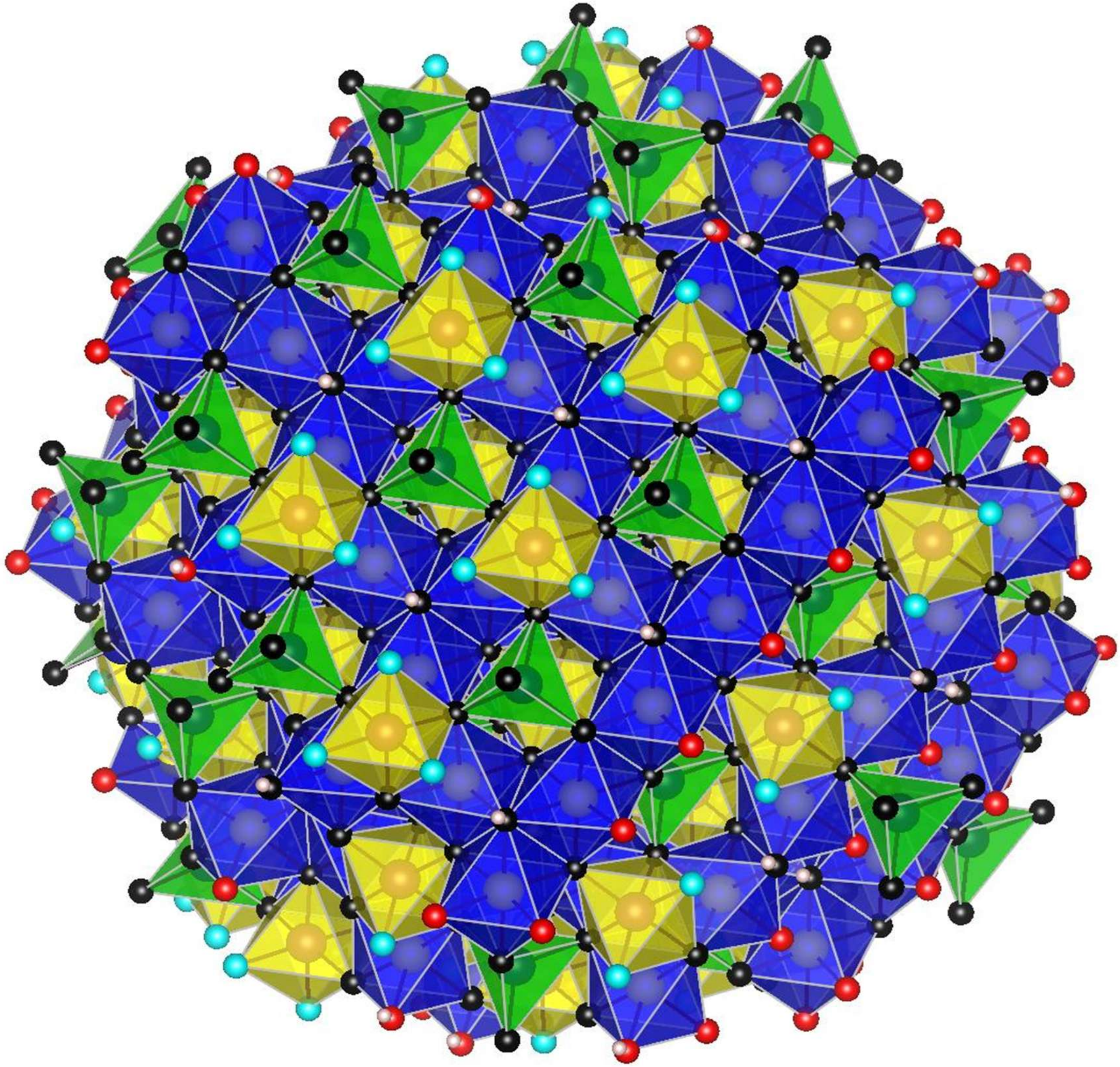
Confined Metastable 2-Line Ferrihydrite for Affordable Point-of-Use Arsenic Free Drinking Water

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*

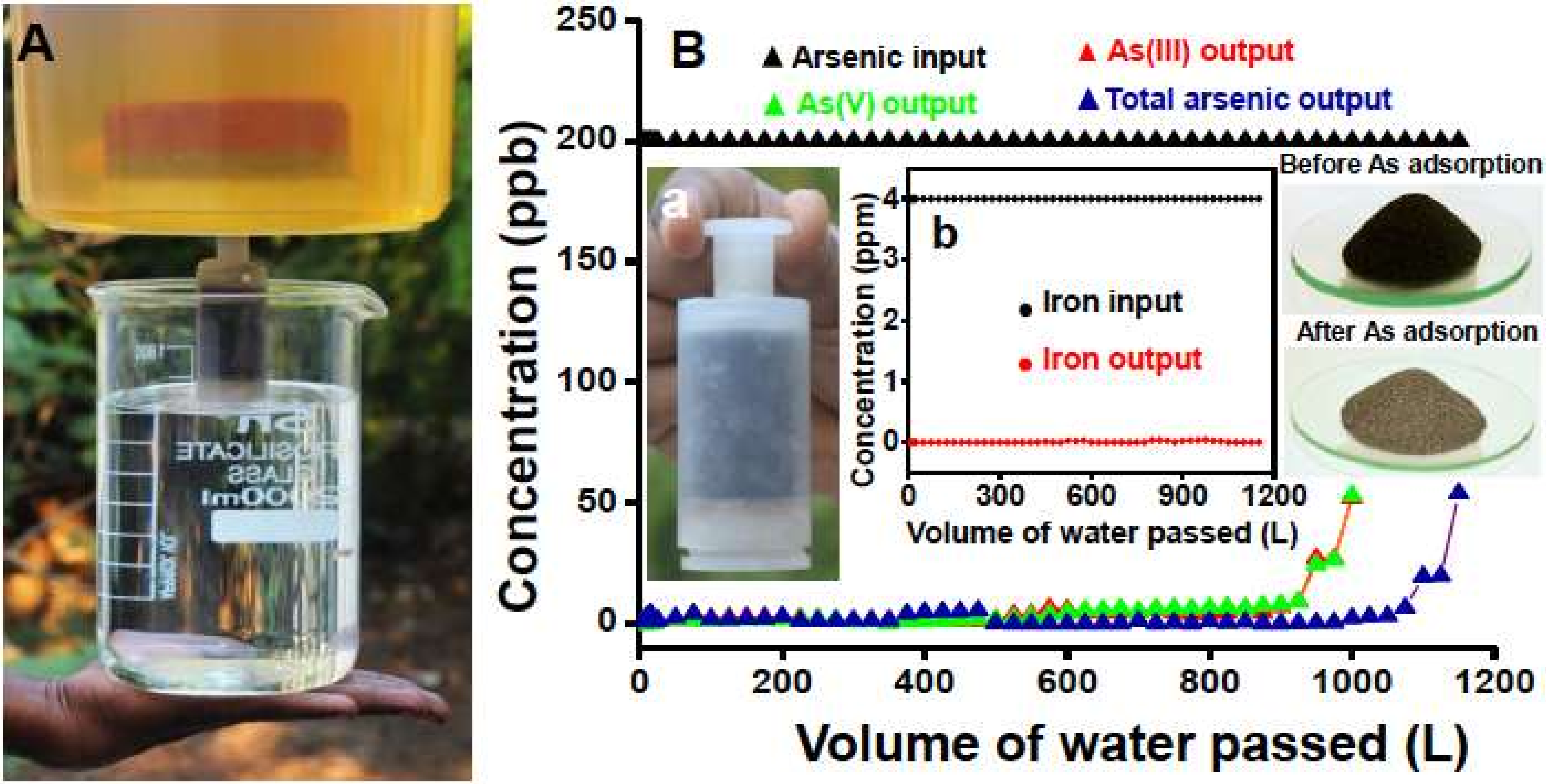
A. Anil Kumar, et. al. *Adv. Mater.*, 29 (2016) 1604260.

Mechanism


A
Fe2p3/2
711.1
Fe2p1/2
724.6
710.0
723.5
708.9
722.3
Intensity (counts)
B
As3d
45.4
As(V)
44.9
44.5
As(III)
44.3
C
As(V)aq
As(III)aq
Binding Energy (eV)
Raman Shift (cm-1)

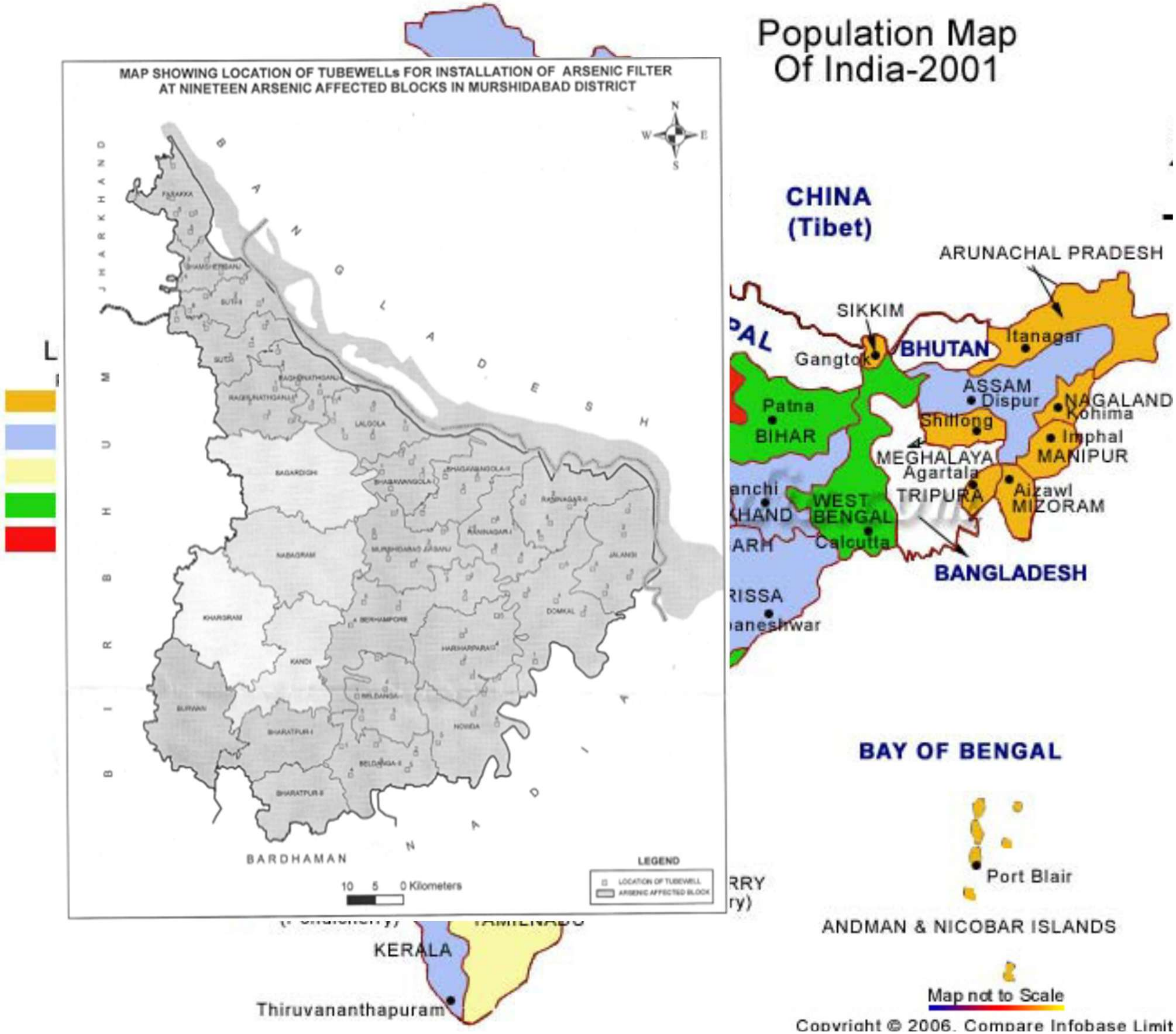


Chennu Sudhakar, et al. *ACS Sustainable Chemistry & Engineering*, 6 (2018) 9990-10000



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


AMRIT
DRINKING WATER
ARSENIC & METAL REMOVAL BY INDIAN TECHNOLOGY
INDIAN INSTITUTE OF TECHNOLOGY MADRAS



Population Map
Of India-2001
CHINA
(Tibet)
ARUNACHAL PRADESH
SIKKIM
Gangtok
BHUTAN
Itanagar
ASSAM
Dispur
NAGALAND
Kohima
Shillong
Imphal
MANIPUR
MEGHALAYA
Agartala
TRIPURA
Aizawl
MIZORAM
Patna
BIHAR
WEST
BENGAL
Calcutta
BANGLADESH
BAY OF BENGAL
Port Blair
ANDMAN & NICOBAR ISLANDS
KERALA
Thiruvananthapuram
Map not to Scale
MAP SHOWING LOCATION OF TUBEWELLs FOR INSTALLATION OF ARSENIC FILTER
AT NINETEEN ARSENIC AFFECTED BLOCKS IN MURSHIDABAD DISTRICT
N
W
E
S
JHARKHAND
BIRBHUM
BANGLADESH
NADIA
BARDHAMAN
10 5 0 Kilometers
LEGEND

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)

Seeing how the new adsorbents are changing the dynamics at the ground level (type 1 of our efforts)

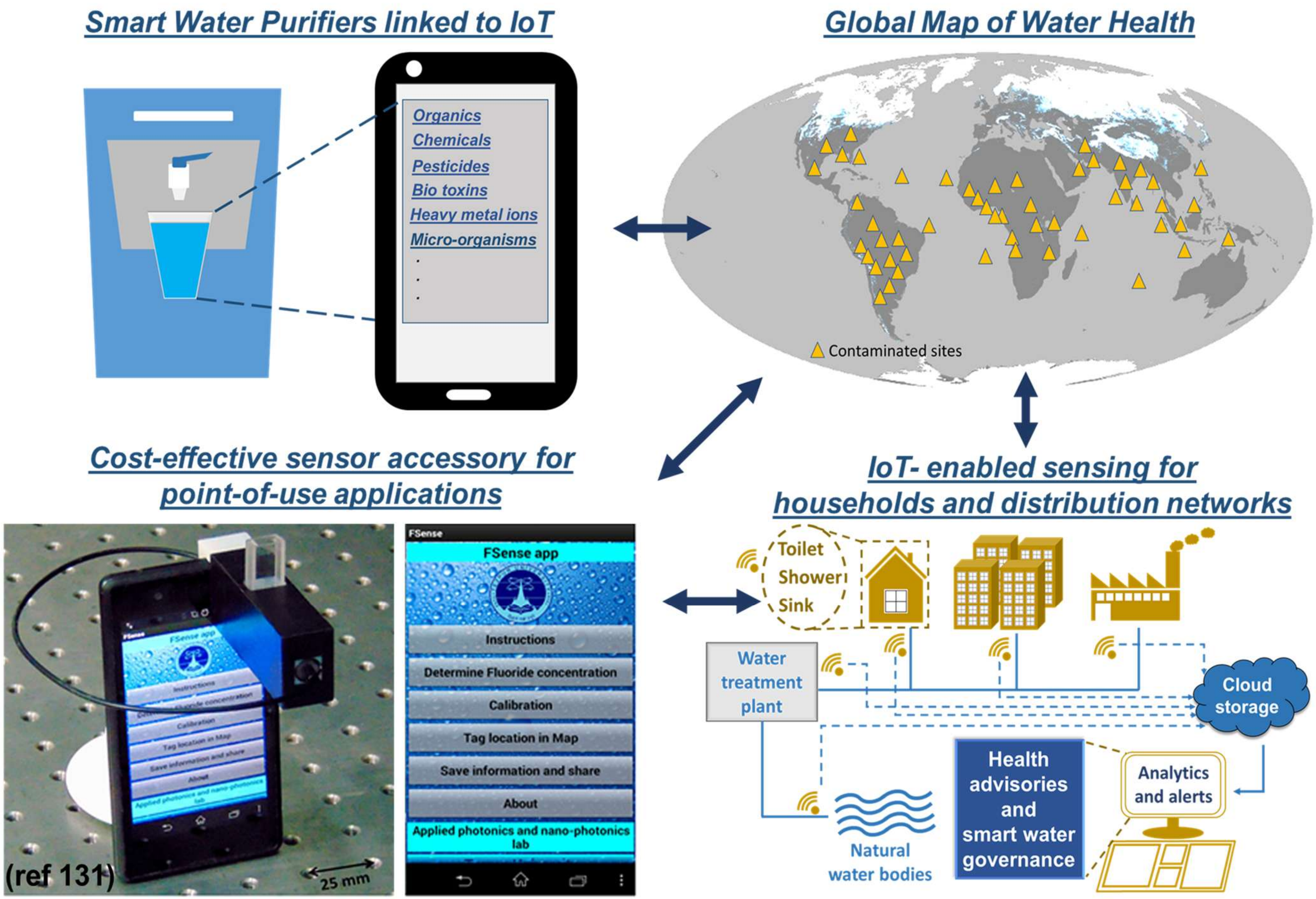
Name of the scheme: Mahilan Wala (TW9144), District: Amritsar
Population: 2610, Daily demand@70 LPCD: 188 kLD, OHSR Capacity: 100 kL

Cleanwater 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	
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

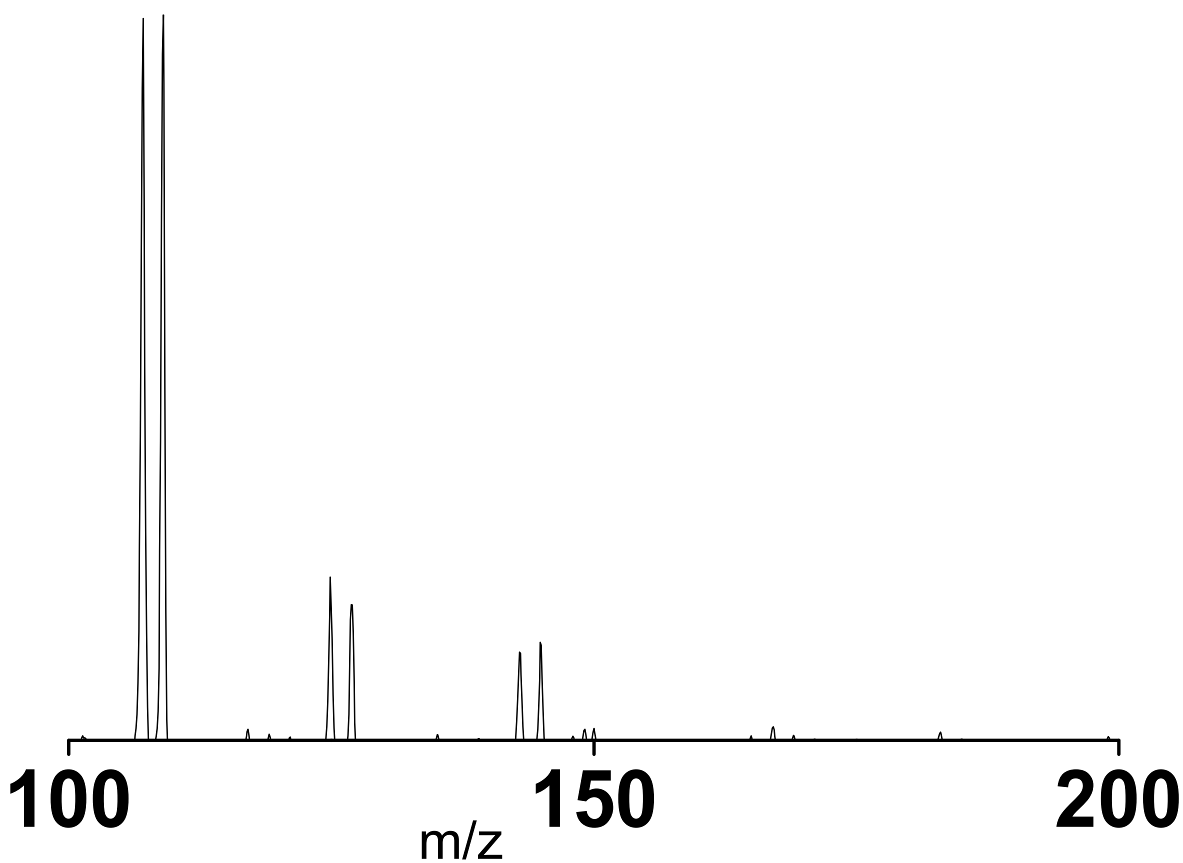
Elemental waste goes back to local environment

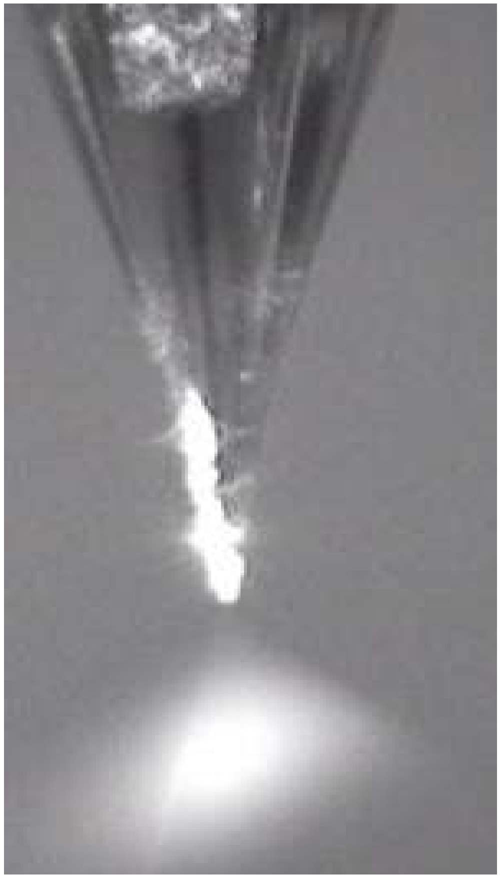
Safe disposal of arsenic (or any other) laden waste

Additional protection could be considered, if necessary

Exploring viable uses

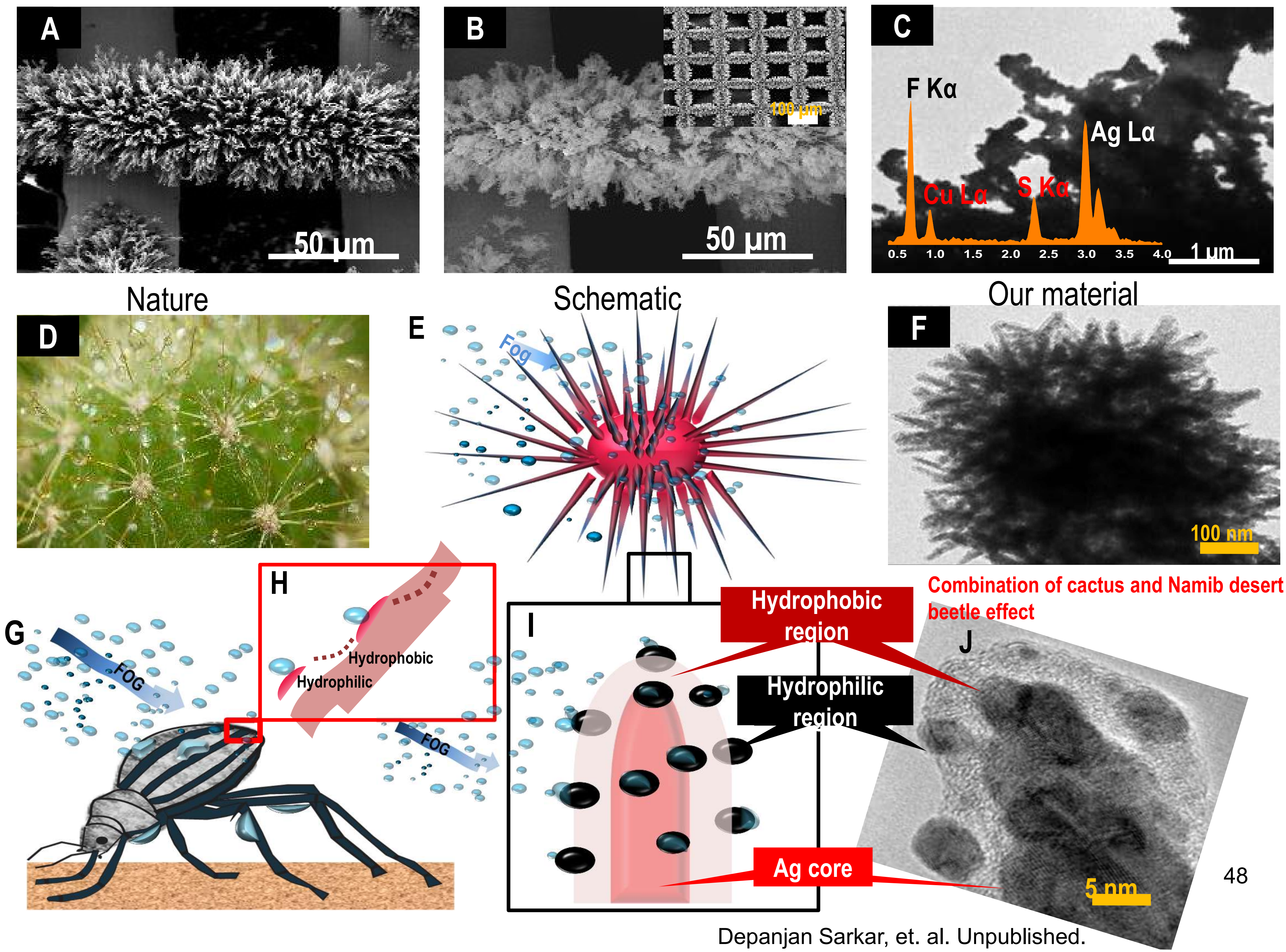
Atmospheric water harvesting



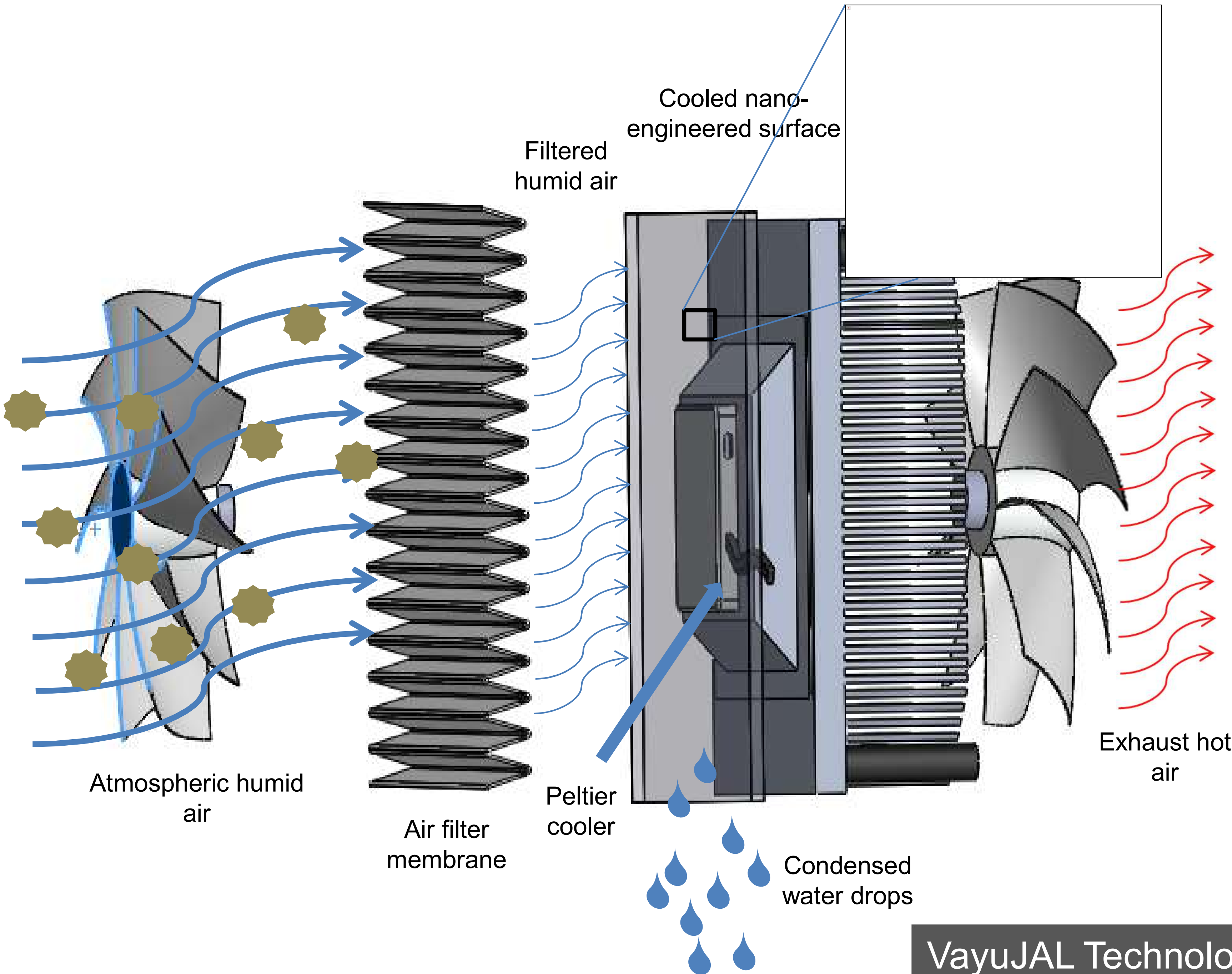


New harvesters

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



Depanjan Sarkar, et. al. Unpublished.



VayuJAL Technologies Pvt. Ltd.

Ramesh Kumar Soni and Ankit Nagar

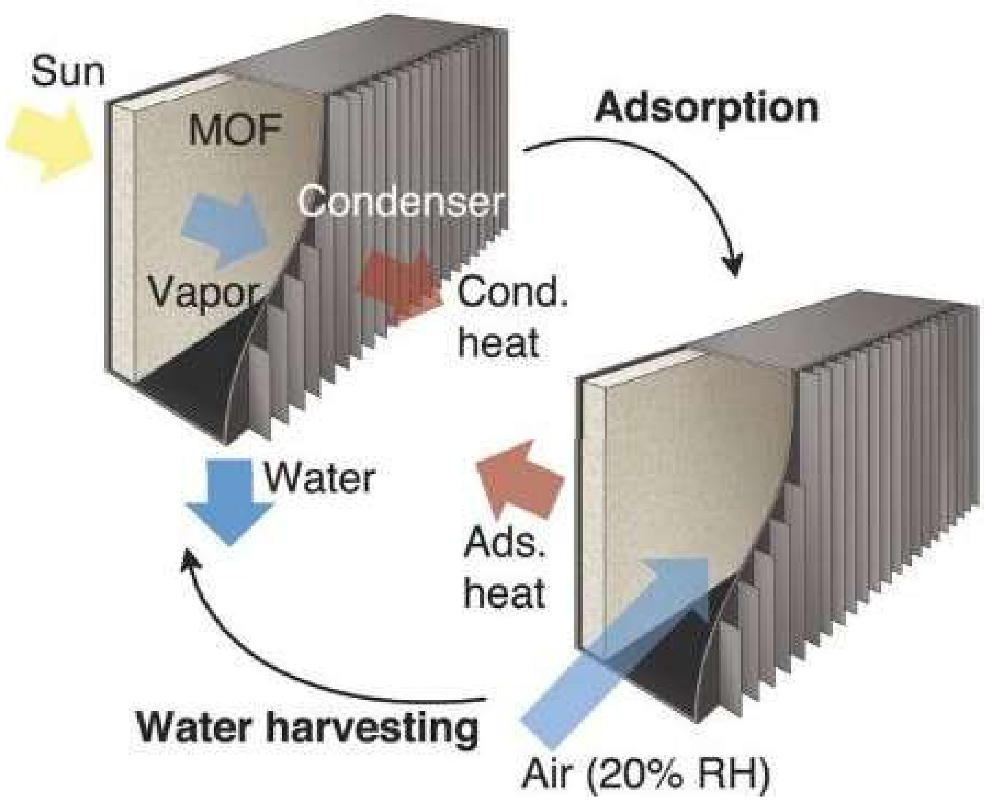
Products in the field

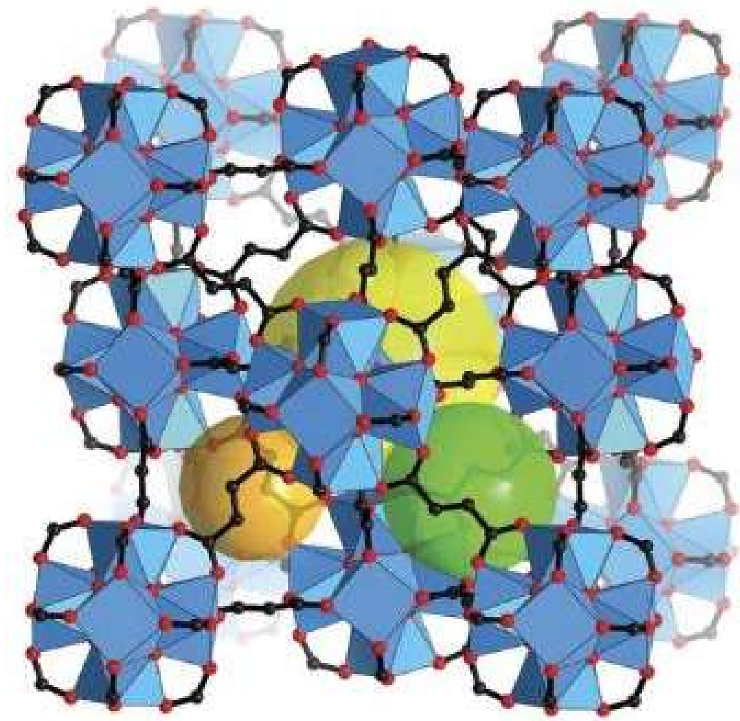
35 LPD 120 LPD 400 LPD 1000 LPD 2000 LPD

(LPD: Litres per day)

Sustainable atmospheric water harvesting

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

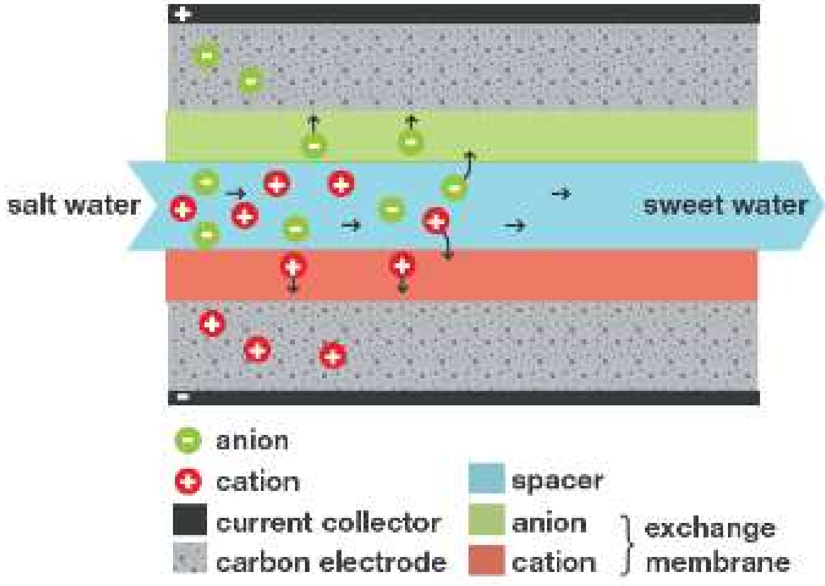


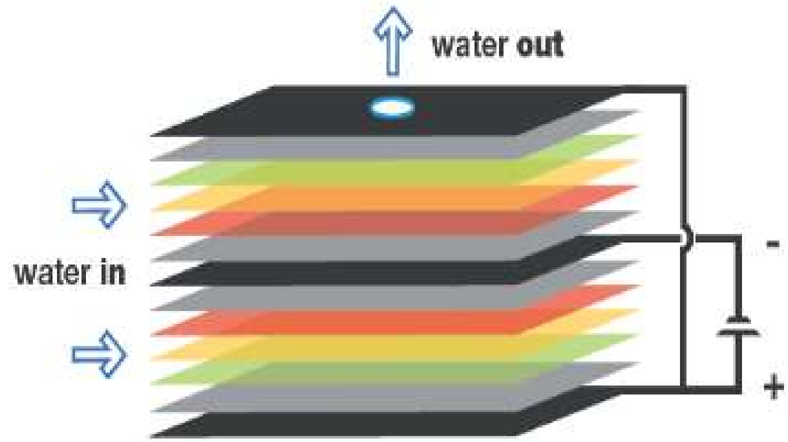


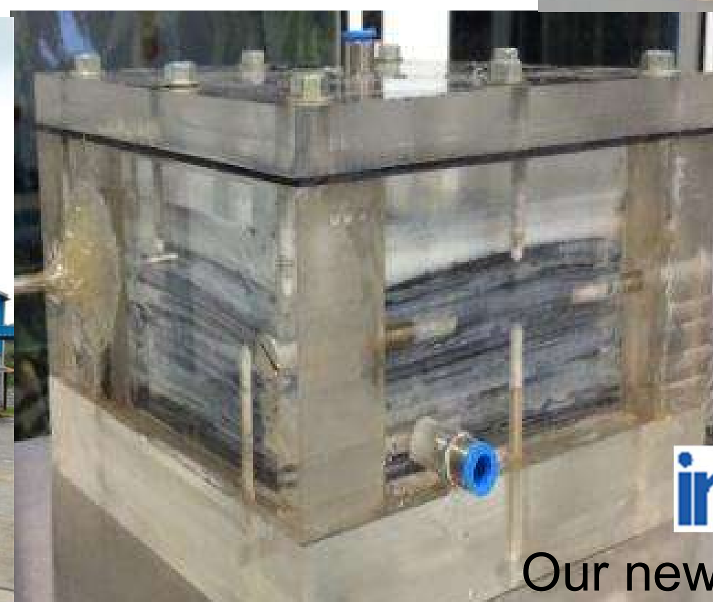
Porous metal-organic framework (MOF-801, $Zr_6O_4(OH)_4(fumarate)_6$)

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

Capacitive Desalination (CDI)

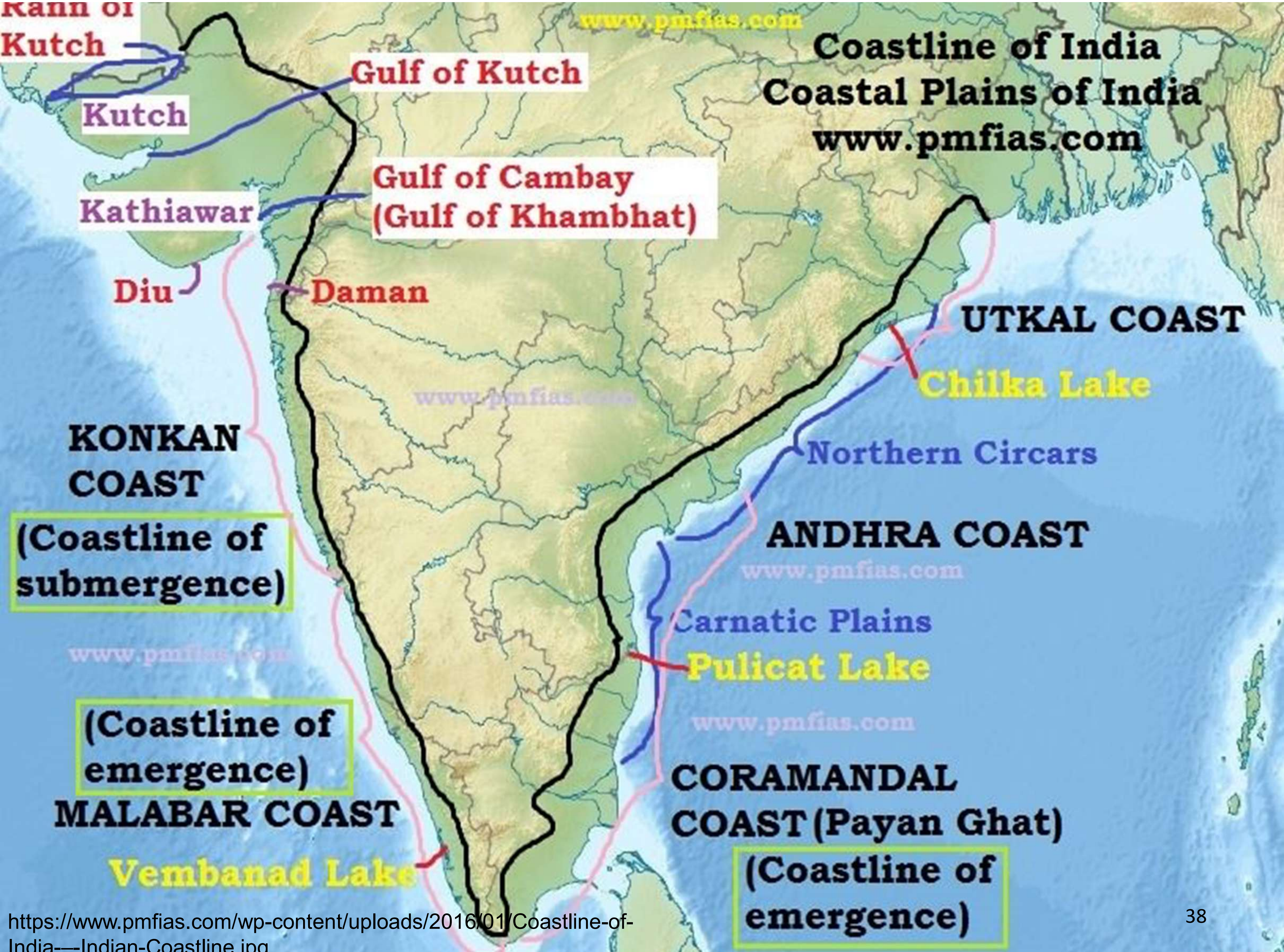




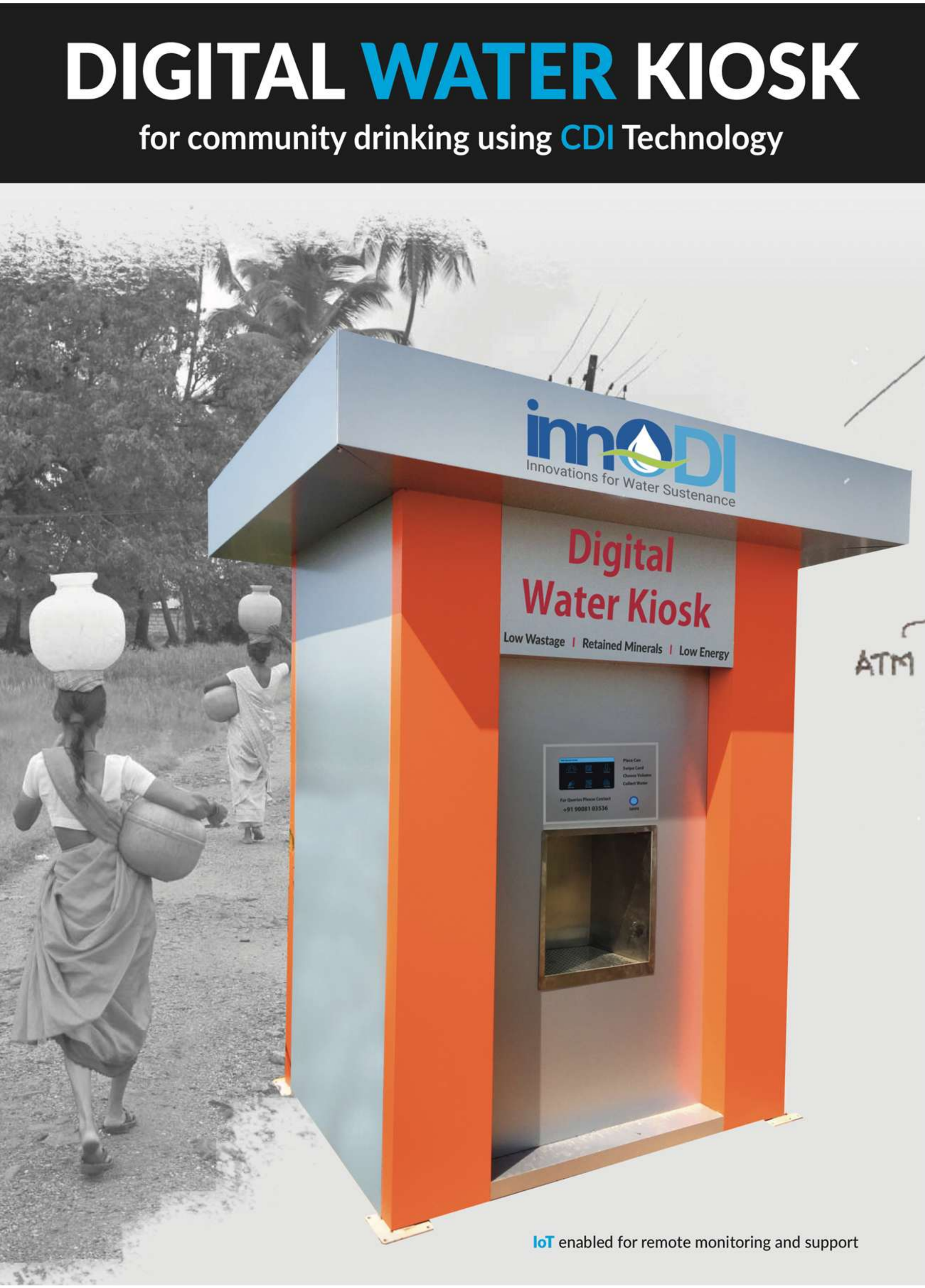


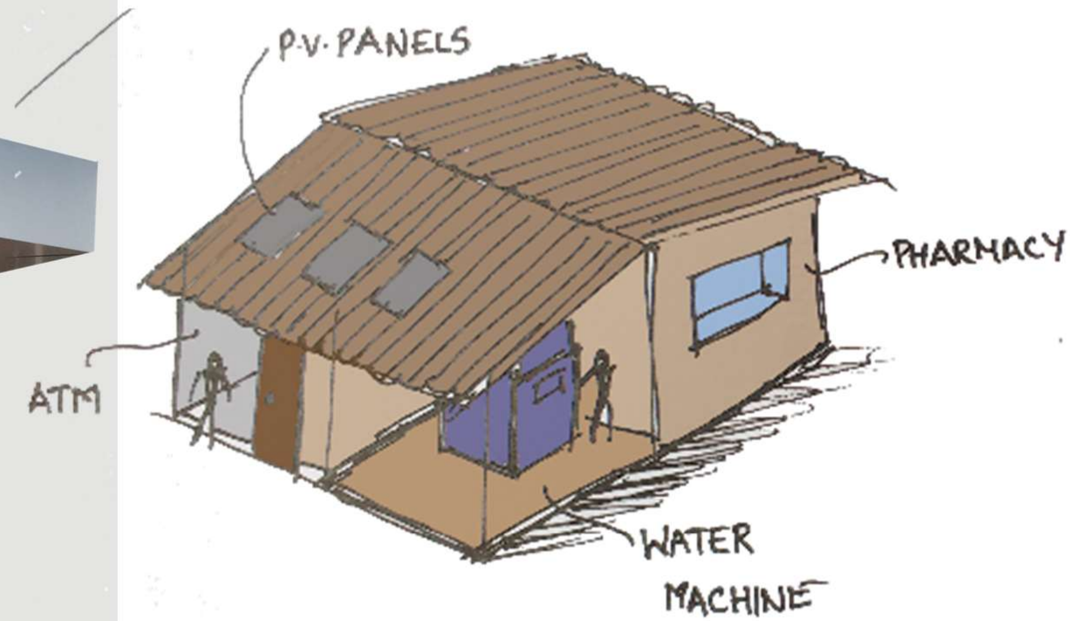
Our new company

Soujit Sengupta, Rabiul Islam and others



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

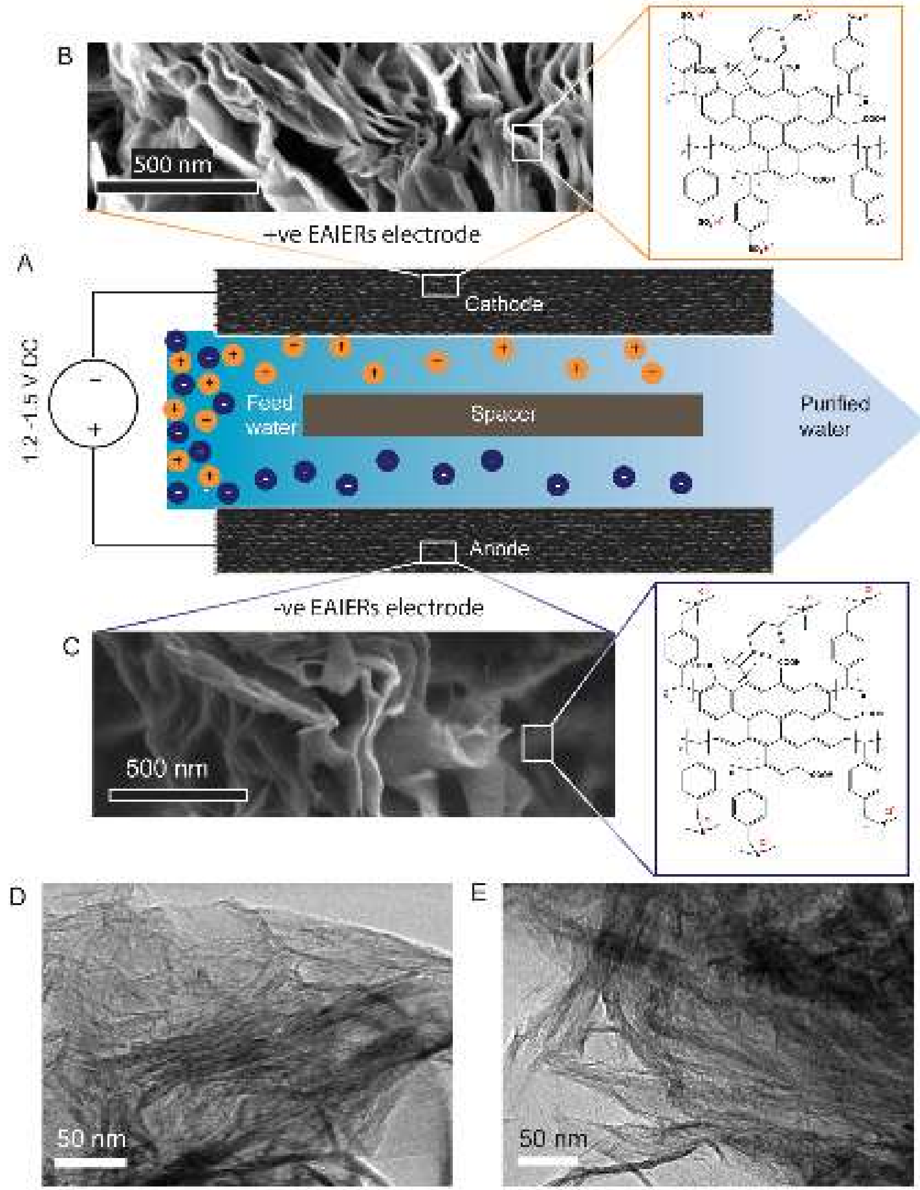




Products under implementation

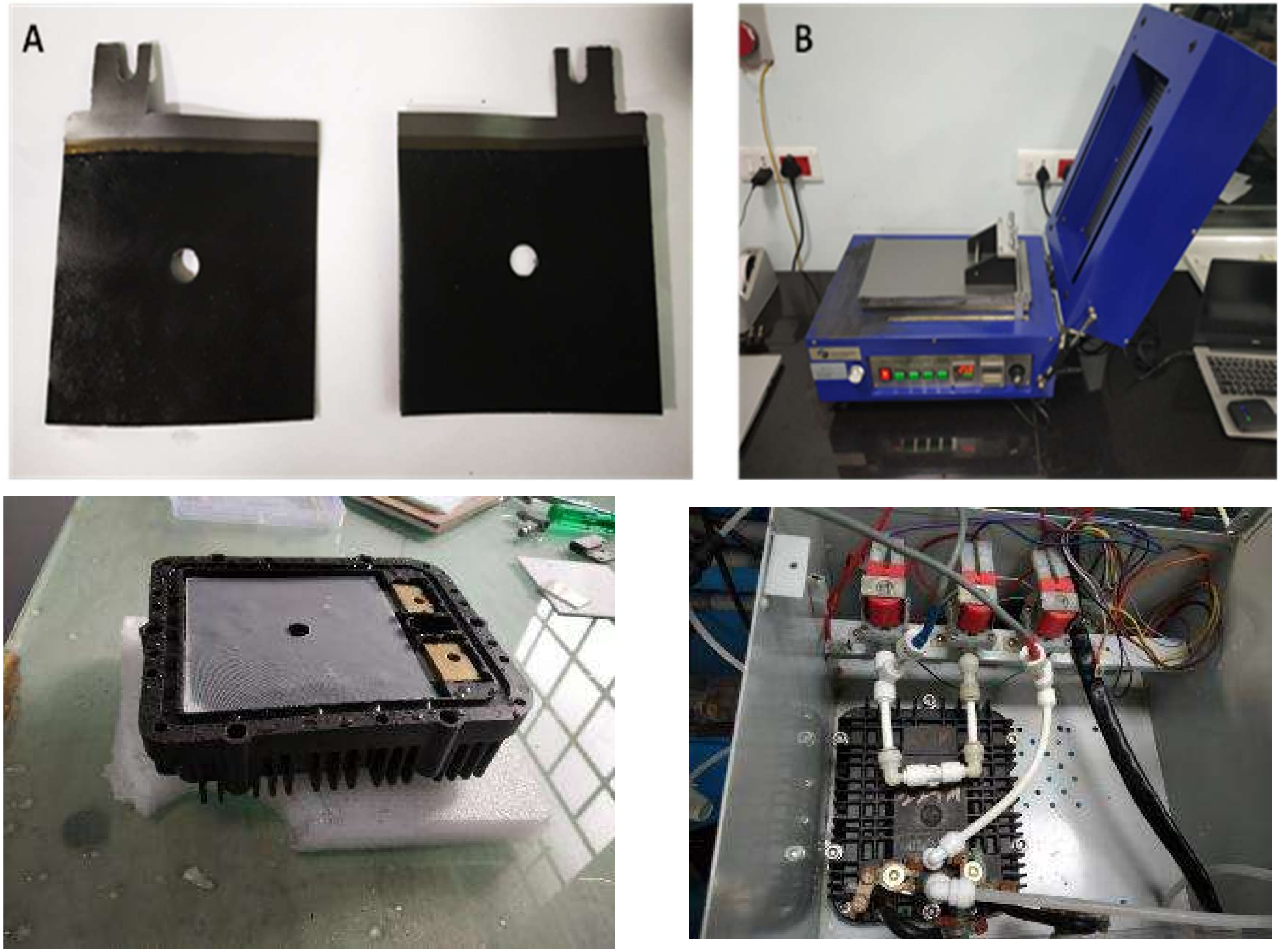
Vijay Sampath and Tullio Servida

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

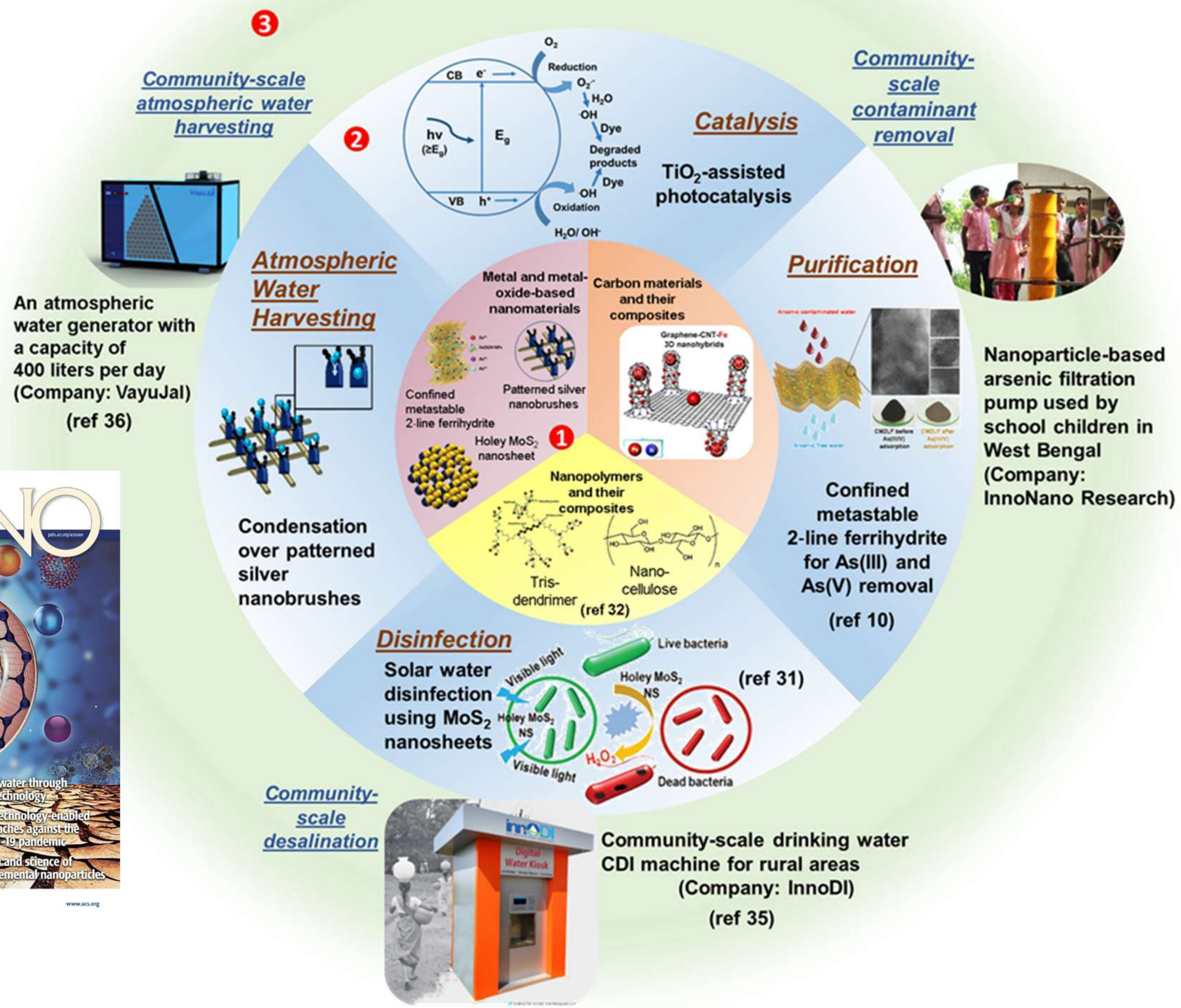


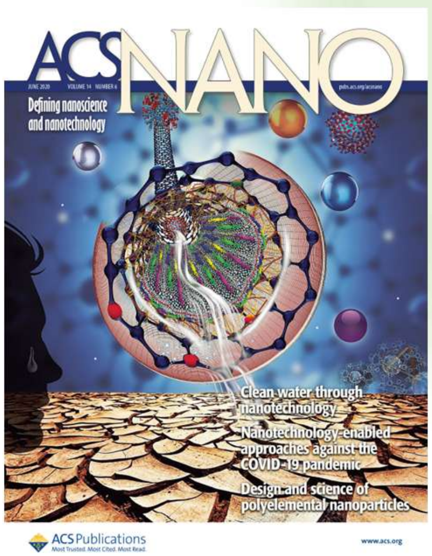
Rabiul *et al., Adv. Mater. Interfaces* **2021**, *8,* 2001998

Various stages of electrode preparation



Evolution of materials to products

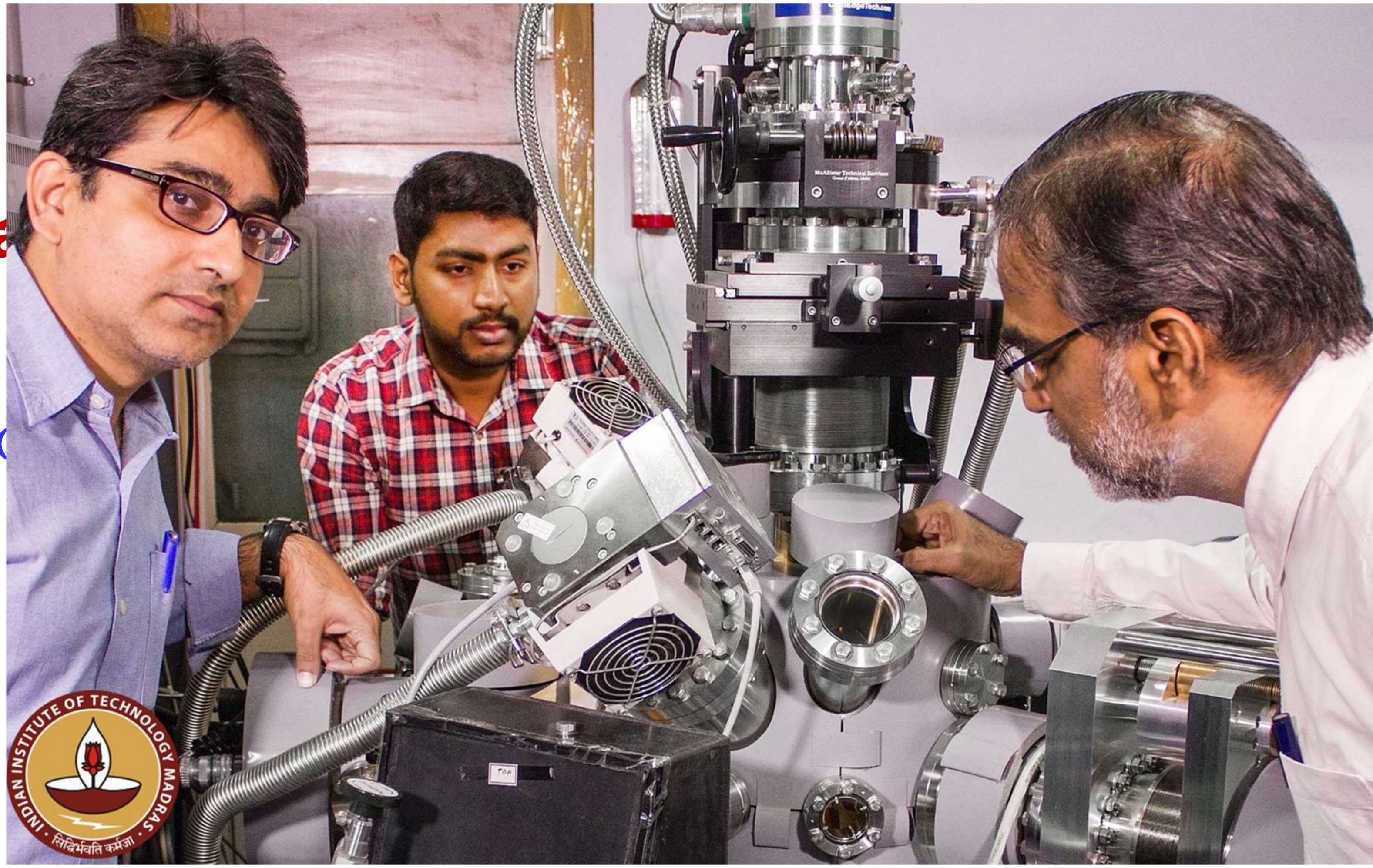




Ankit Nagar and T. Pradeep 14(2020). *ACS Nano*, 6420-6435

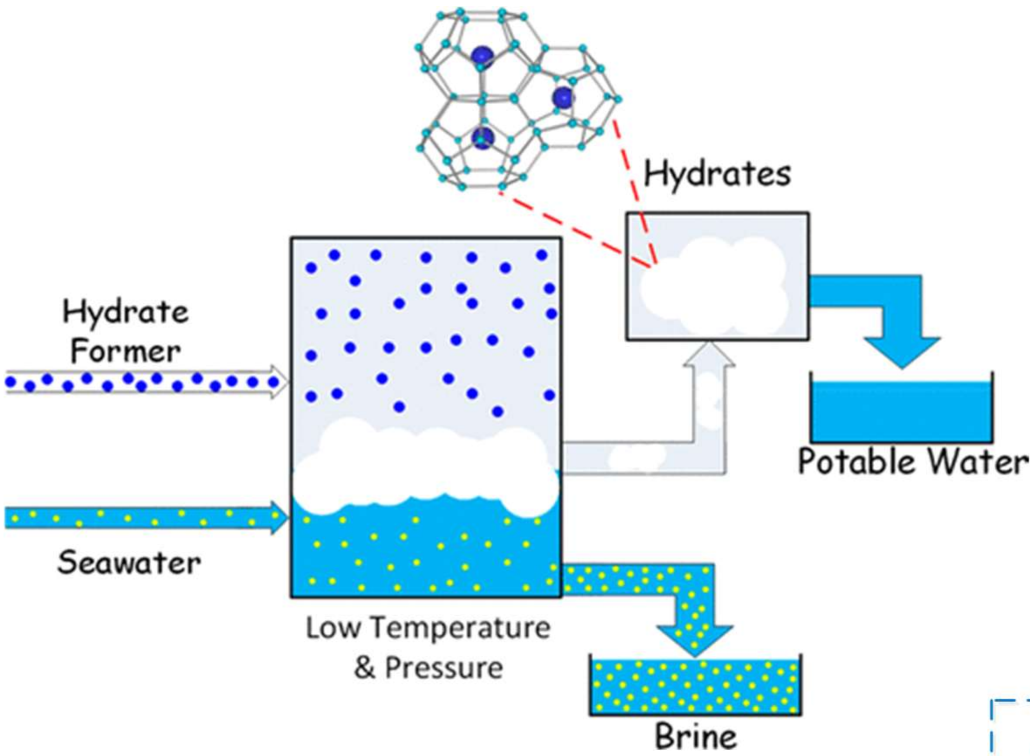
New phenomena

Cla ***ent***



With Rajnish Kumar

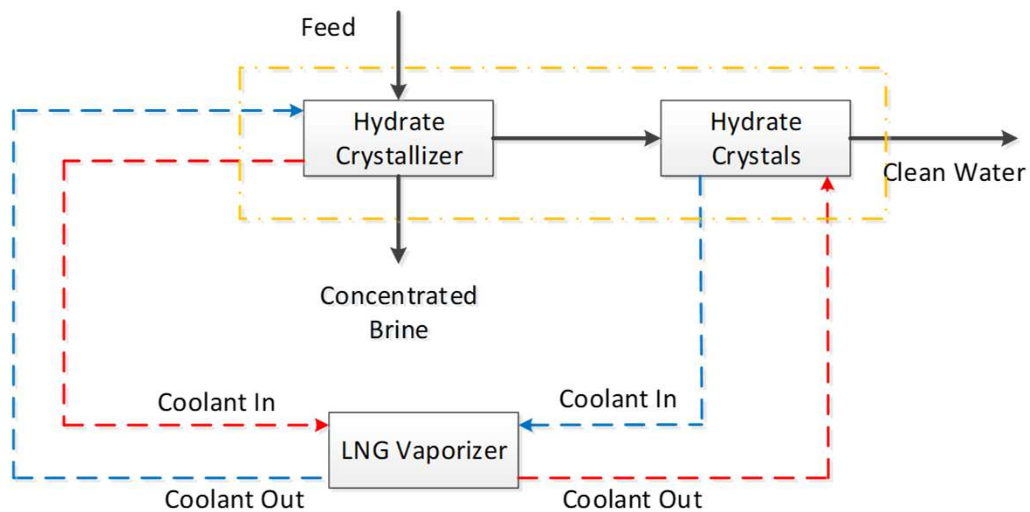
Hydrate-based desalination (HyDesal)



HyDesal process advantages

- ✓ Salts get occluded
- ✓ No chemical reaction, recovery of water is very easy
- ✓ Hydrates consist of 85% water and rest guest gas
- ✓ Not sensitive to impurities or salt concentration

Water dissociated from hydrate is pure

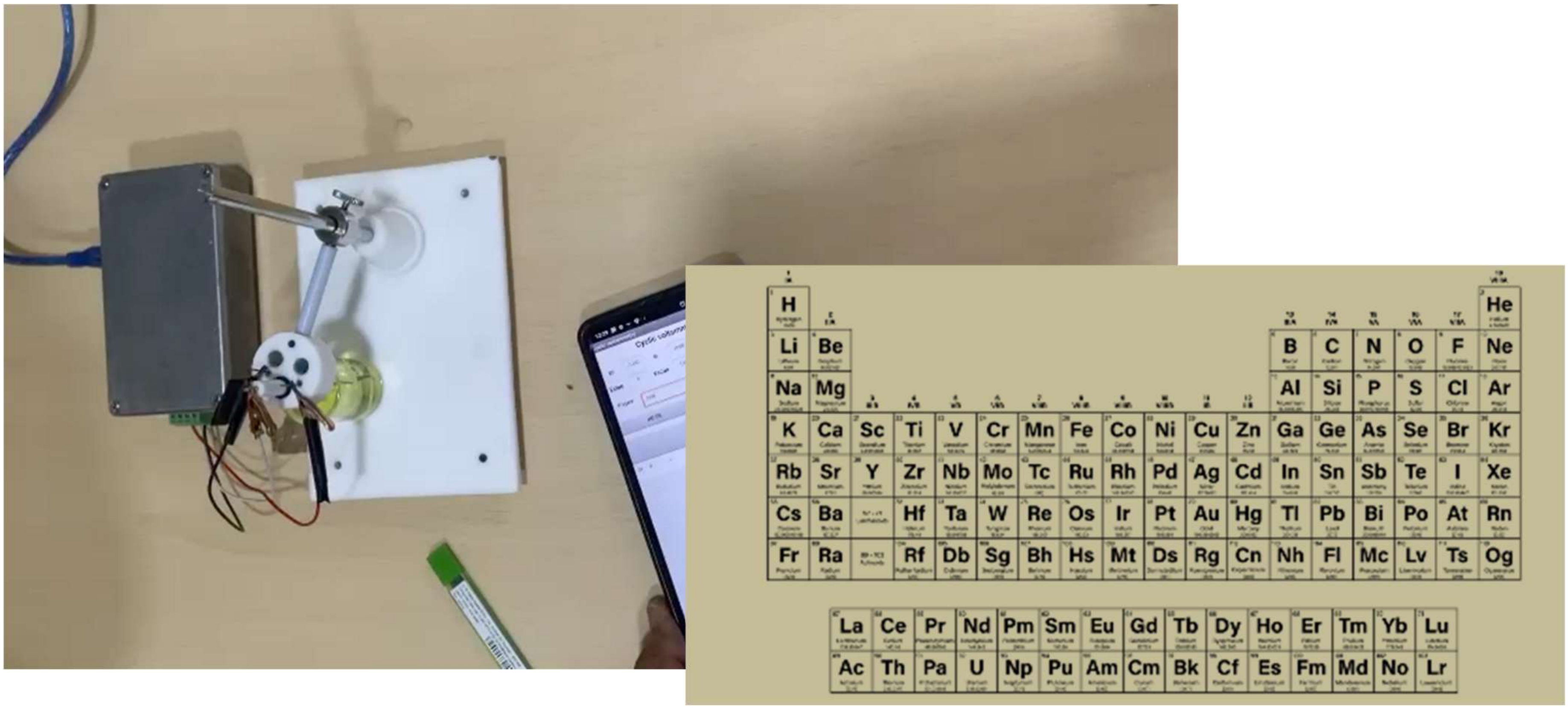


Cold Energy in LNG terminals can be harvested to produce water

Babu et al. ACS Sustainable Chemistry and Engineering (2018), 6 (7), 8093-8107

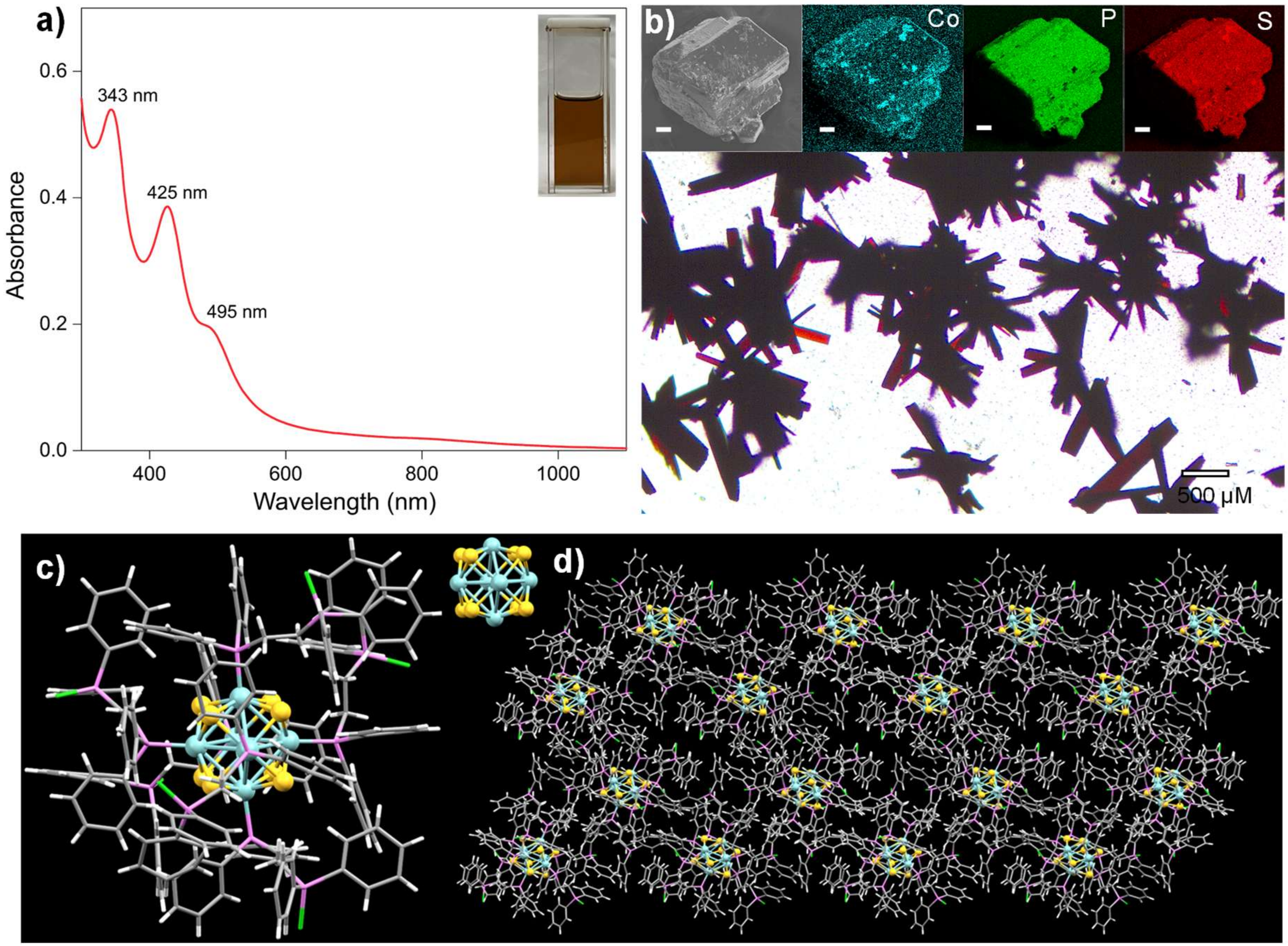
Slide from Prof. Praveen Linga, NUS

Analytical devices



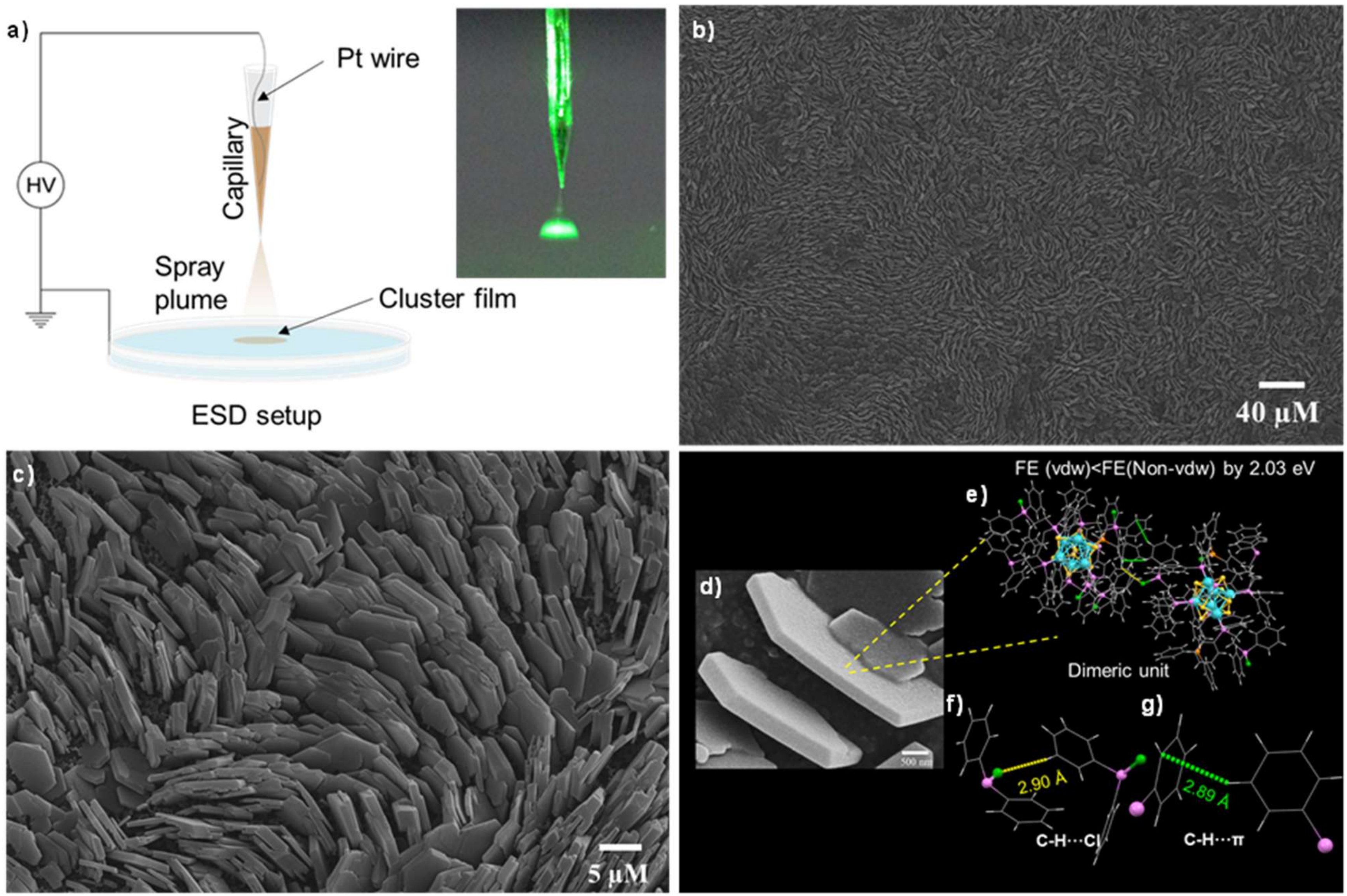
Sourav Kanti Jana

New electrodes - Aligned nanoplates

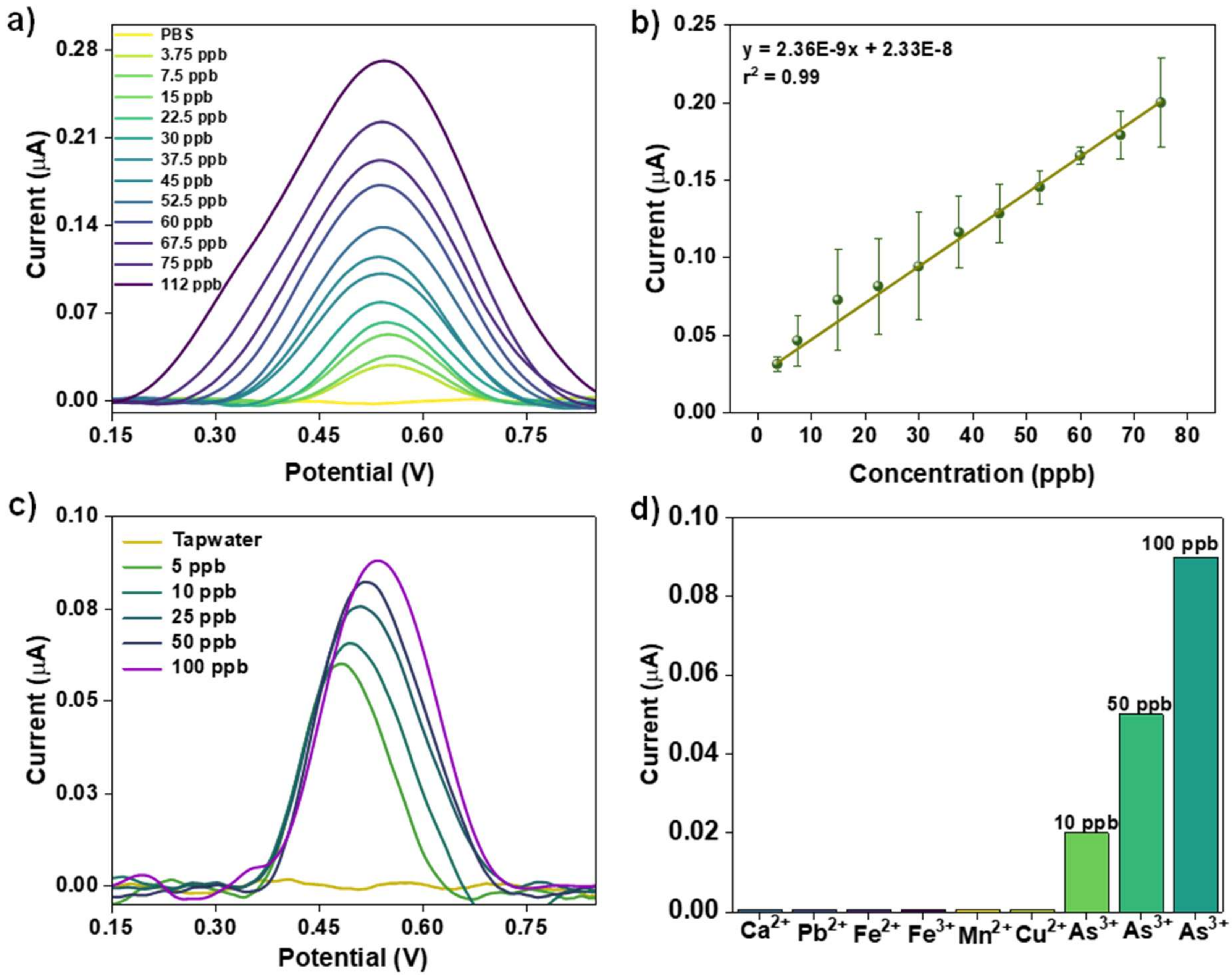


Anagha Jose et al, 2022 (unpublished)

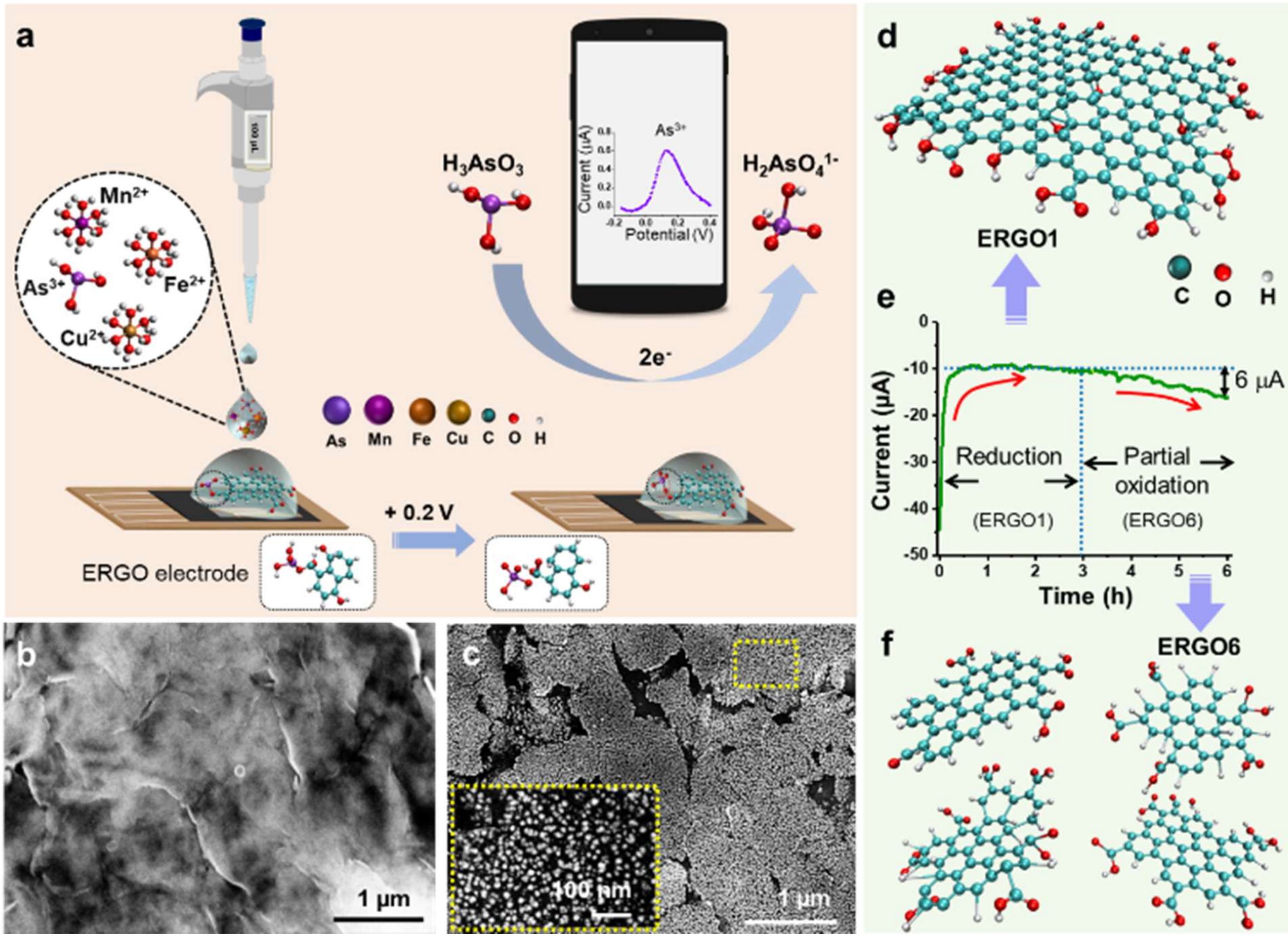
Electrospray deposition



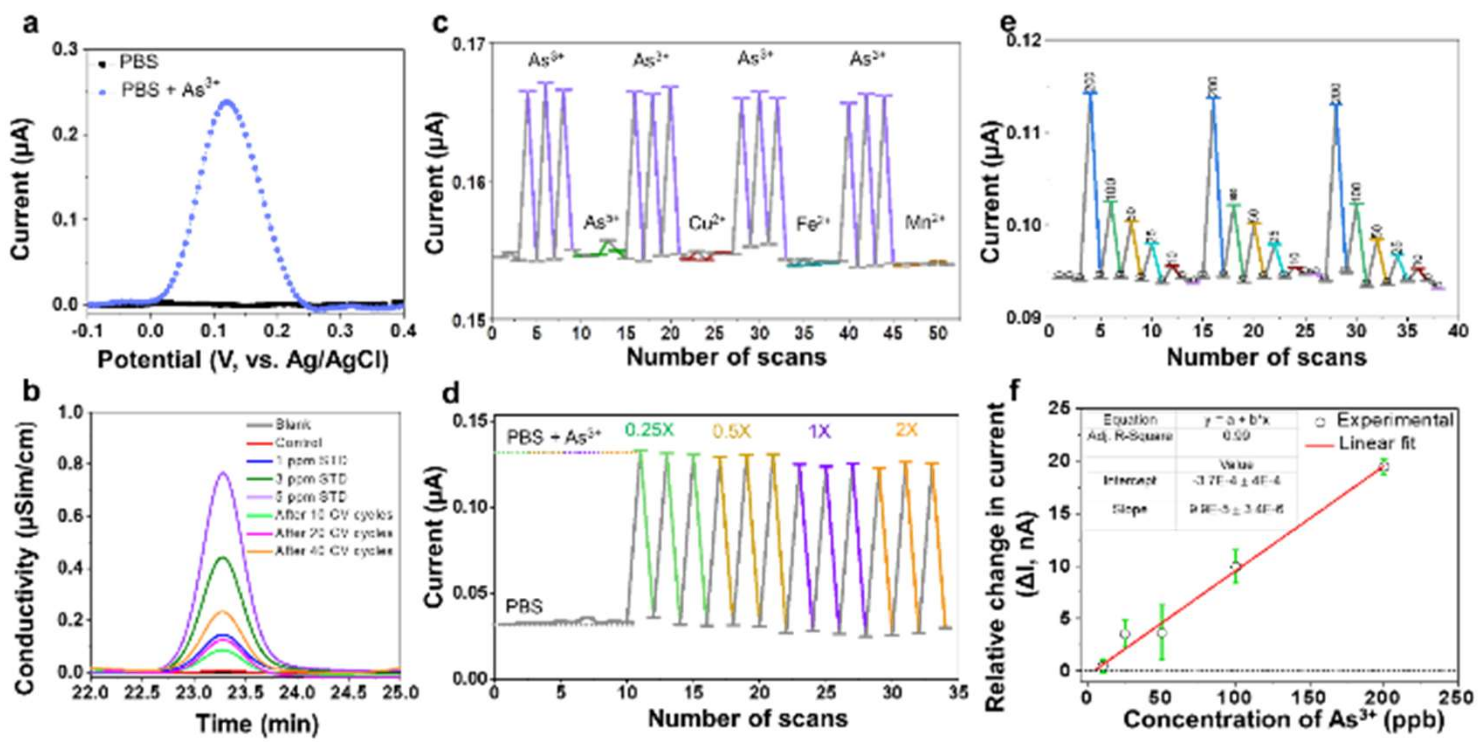
Sensing


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⁺

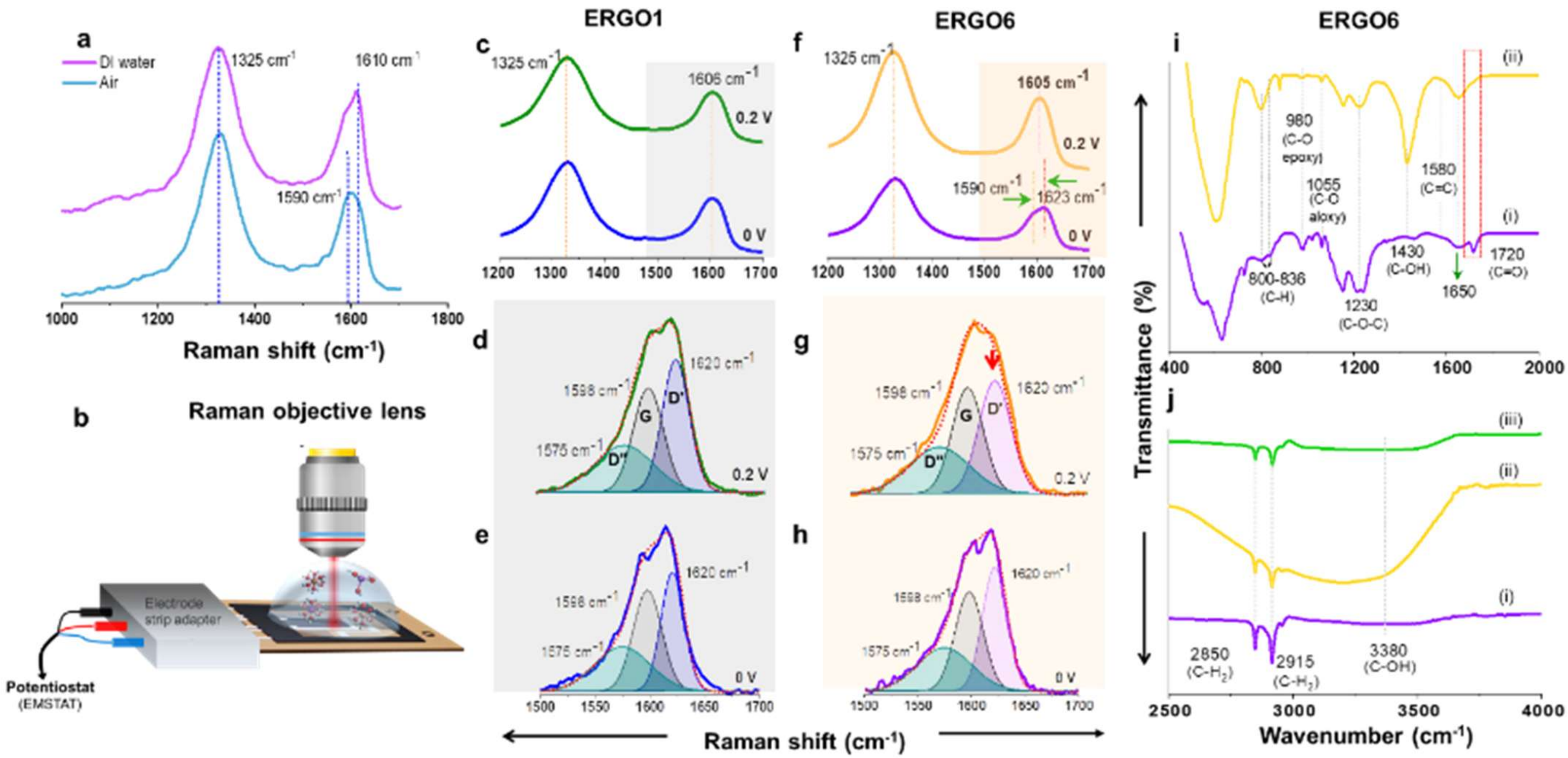
Practical graphene-based arsenite sensor at 10 ppb



S. K. Jana et al. ACS Appl. Nano Mater., 5 (2022) 11876−11888.

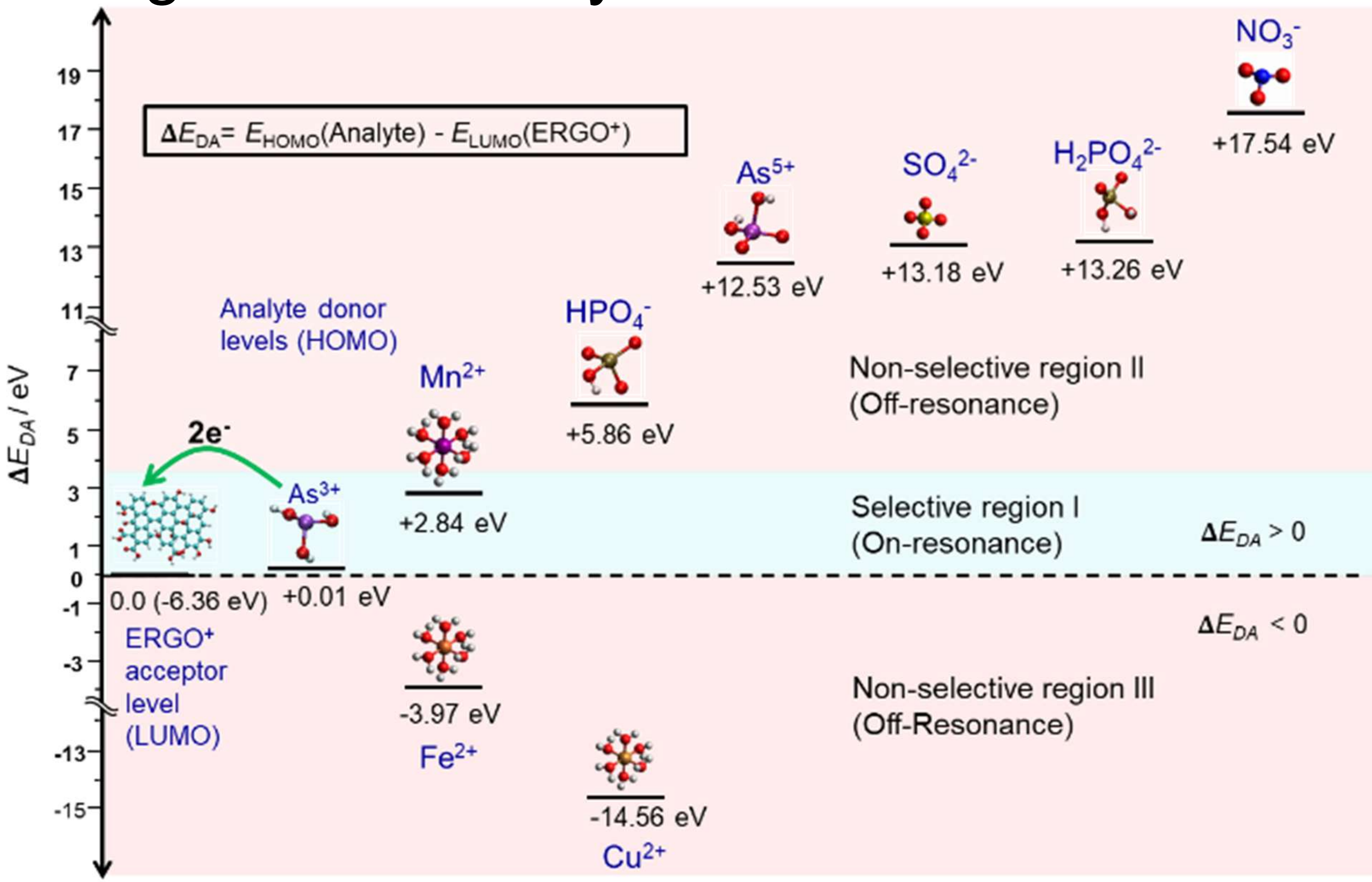


(a) LSV response of ERGO6 without and with 1 ppm As^{3+}, (b) Chronograms obtained from ion chromatography (IC) measurement with the solutions obtained after different number of CV cycles and same measurement with standard (STD) As^{5+} solutions of different concentrations. (c) CA measurement with different concentrations of As^{3+}. (d) Calibration curve showing linearity down to 10 ppb. (e) Interference study performed with several heavy metal ions with ERGO6 electrode. Concentration of As^{3+} was fixed at 200 ppb, while 1 ppm was maintained for interfering ions. (f) Investigation of CA current response of 1 ppm As^{3+} spiked in PBS with different ionic conductivity. We prepared PBS solutions of different conductivity by changing their ionic concentrations and used them further as electrolytes during CA measurements.



(a) Raman spectra of ERGO6 without (air) and with DI water. (b) Schematic depicts spectro-electrochemical (SPEC) measurement set-up. During SPEC measurements, the Raman objective was focused at the surface of ERGO6 strips with and without As^{3+} containing DI water on it and a DC potential of 0.2 V was applied to the electrode. (c) Raman spectra of ERGO1 in presence of As^{3+} without and with the application of potential (+ 0.2 V). Gaussian peak fitting was performed on the G bands of Raman spectra of ERGO1 (d) with, and (e) without the application of potential. (f) Raman spectra of ERGO6 in presence of As^{3+} without and with application of +0.2 V. Gaussian peak fitting was performed on the G bands of the Raman spectra of ERGO6 (g) with and (h) without the application of potential. Decrease in the intensity of D′ is marked with a downward arrow. FTIR spectra of ERGO6 (i) without (purple trace) and with As^{3+} (yellow trace), (j) FTIR spectra of the same strip without As^{3+} (purple trace), with As^{3+} (yellow trace), and after electrochemical oxidation (green trace) to show the changes in OH deformation peak at higher wavenumber

Origin of selectivity

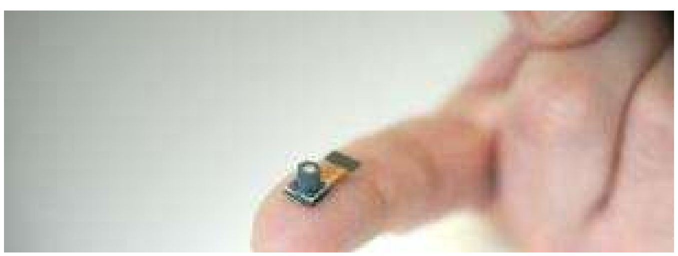


Expanding the reach

Sensors and new opportunities

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

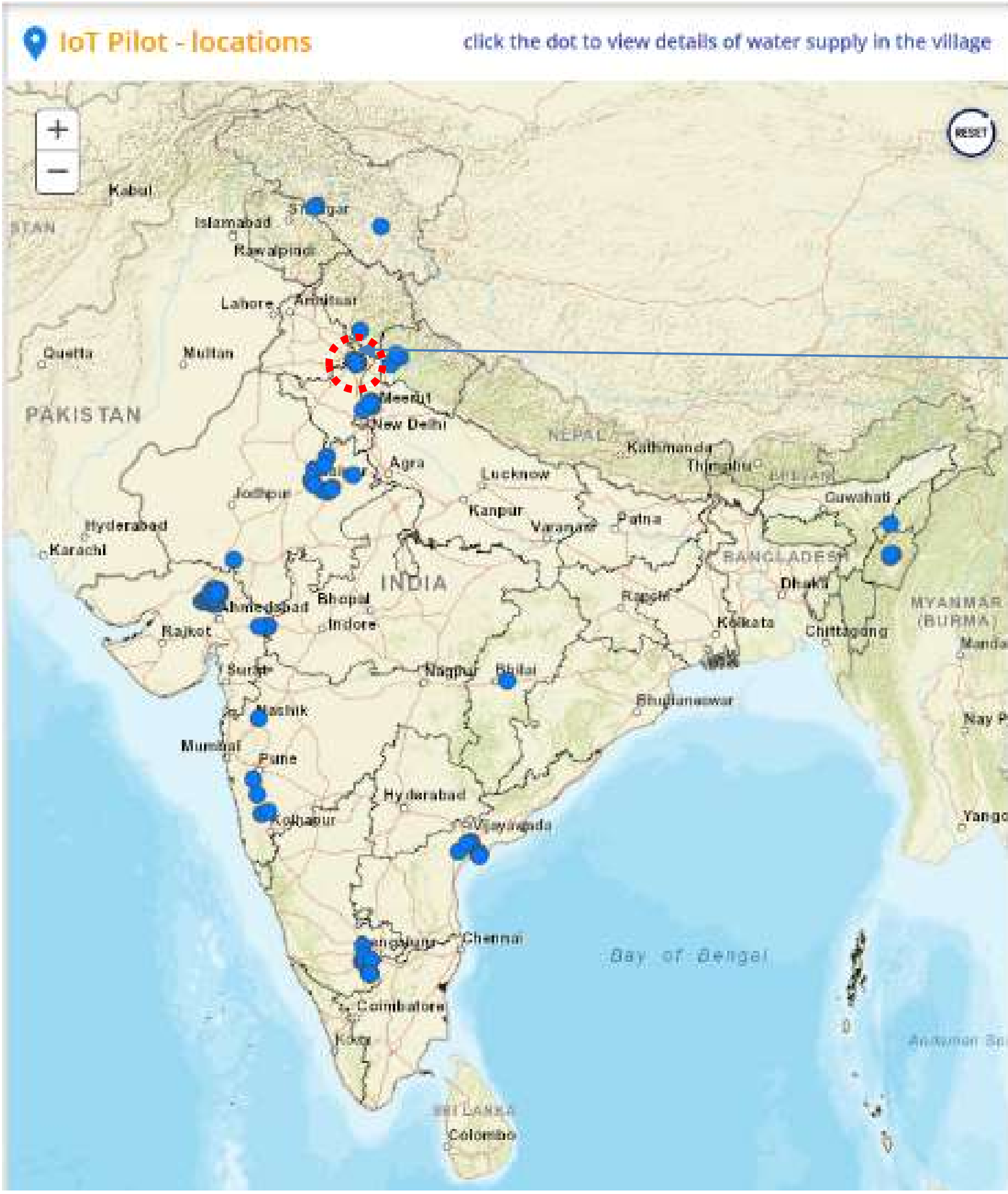
Ultra compact Low Cost
Spectral Sensor Module
~ Billions units (? 2027)



Water quality measurement – In the pipeline

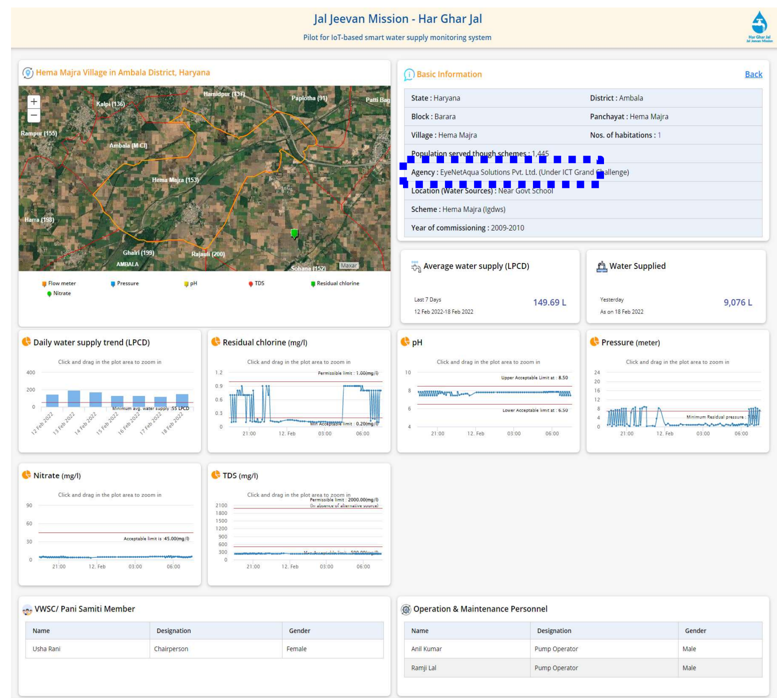
nanoλ

India's water is being monitored



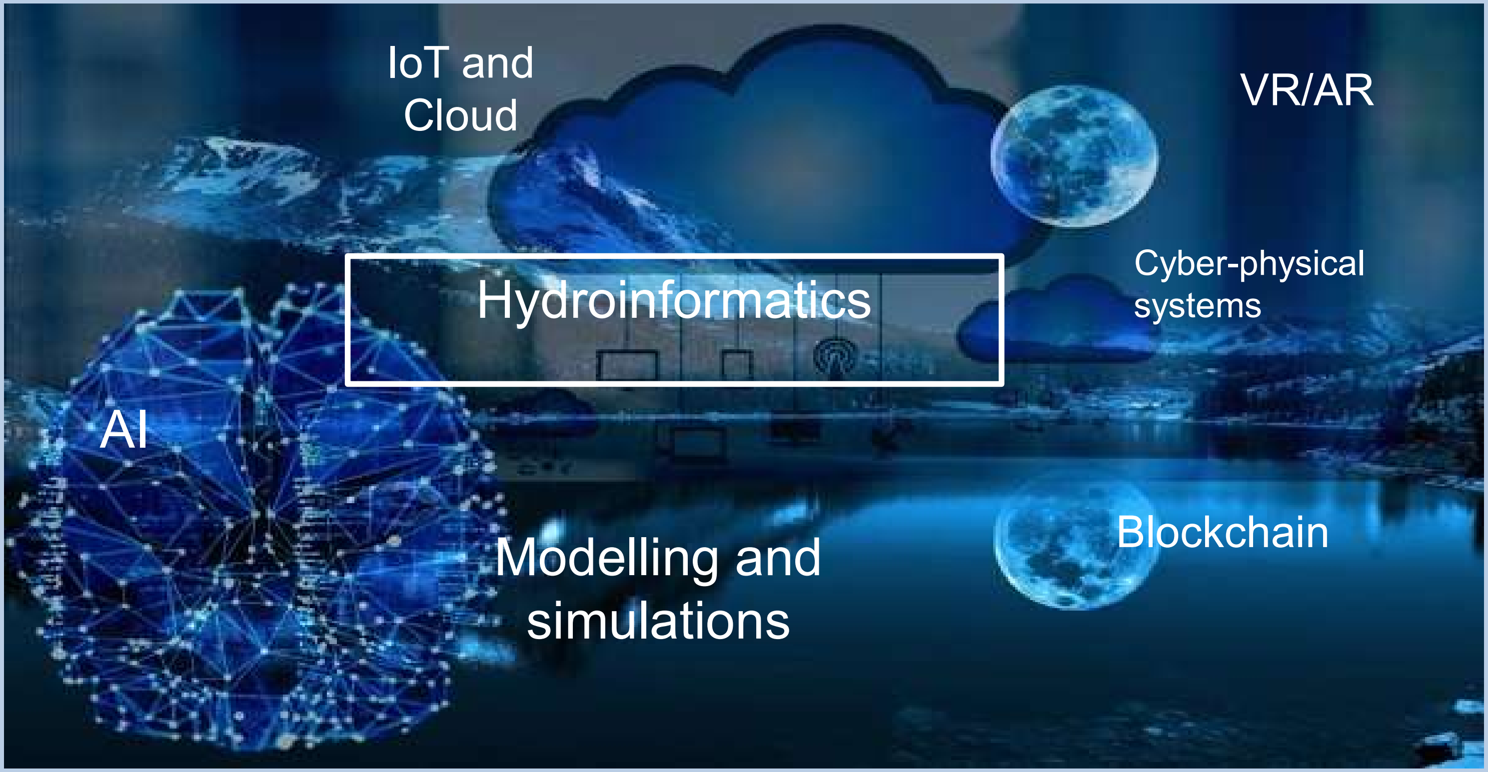
IITM/IISc

Installations made by four companies



Hydroinformatics

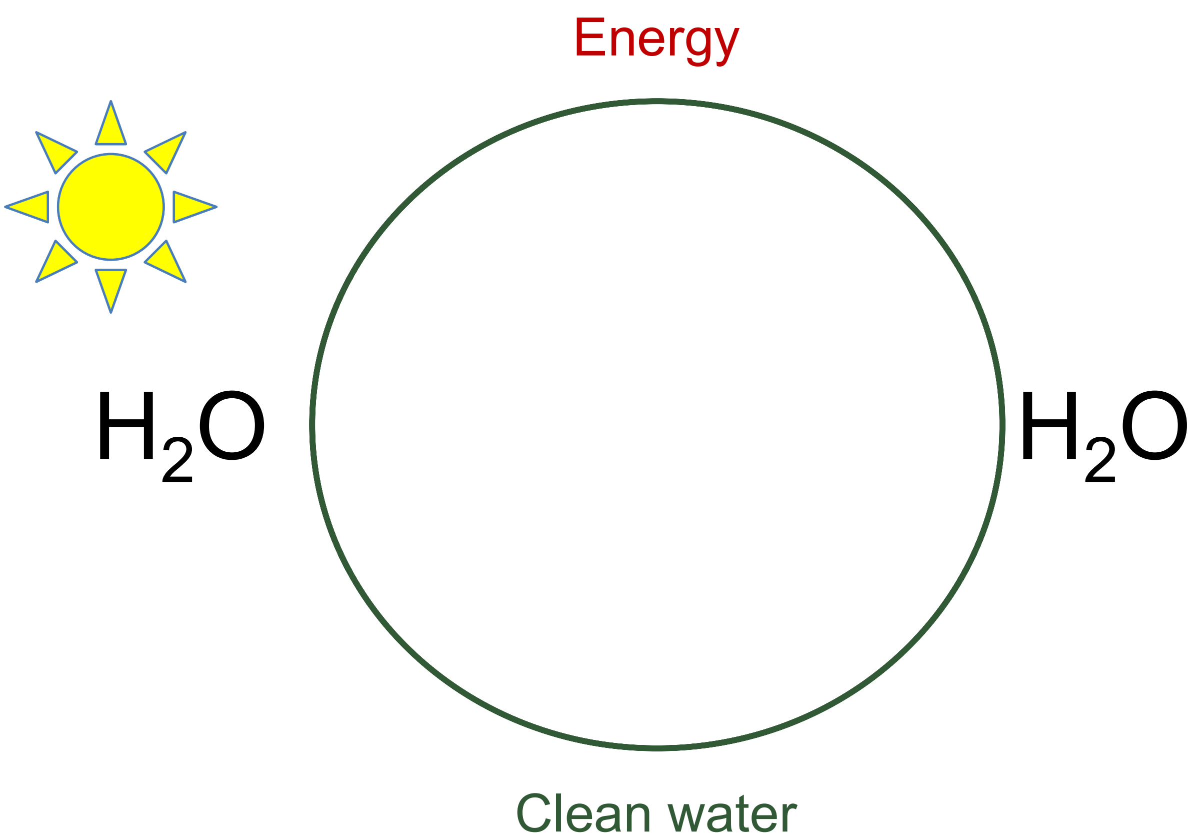
Application of computing technologies for efficient, sustainable and equitable water management.

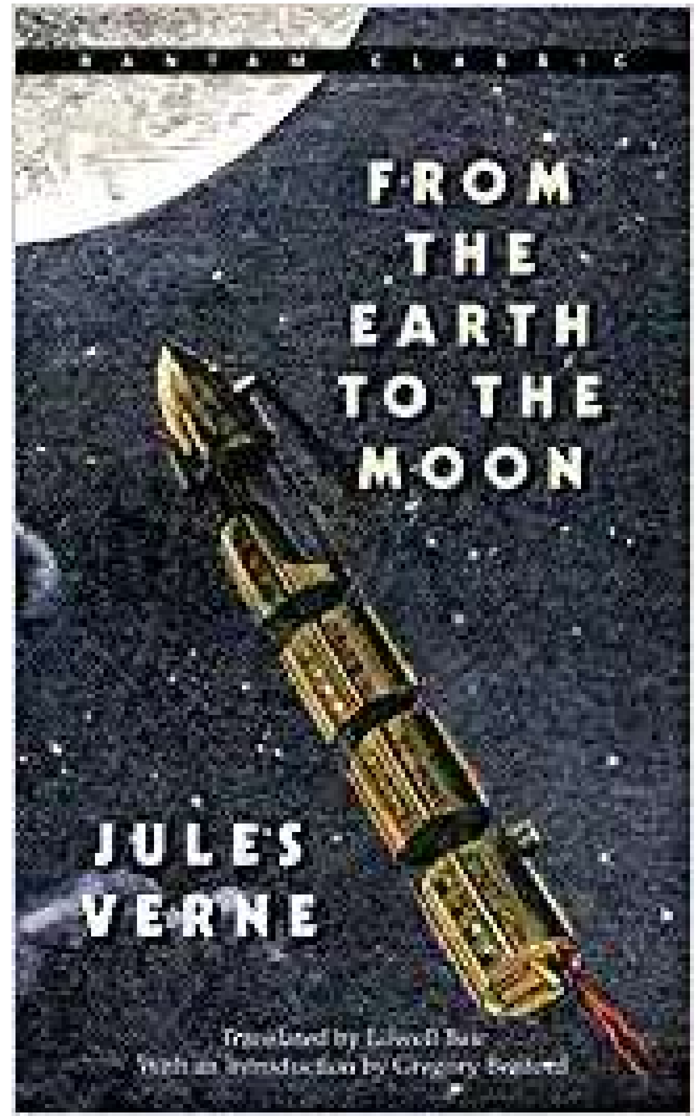


Digital water or water 4.0 will revolutionize water management.


Policy

Our dreams become reality with materials





Affordable, inclusive, sustainable and contextual excellence

Some simple calculations

Hydrogen + Oxygen → Water + 286,000 joules of energy per mole

1 kg of solar hydrogen is now at Rs. XX and could be Rs. 150 soon.

It can make 143 million J of energy.

Desalination needs 2.4 kWh or 8.84 million joules for 1 CM of water.

1 kg of hydrogen can therefore make 16.56 CM of water.

Or Rs. 9.06 per cubic meter, 0.9 paise per litre!

Well, add efficiency, other costs of plant, transportation, etc.

That world will need water literacy

International Centre for Clean Water


IIT Madras Research Park
A
B
C

The AMRIT Team, 2013

Group during 2018, along with Prof. Graham Cooks

People: 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,...

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सत्यमेव जयते

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Associate Editor

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THEMATIC UNIT OF EXCELLENCE

Thank you all