جامعة الملك عبدالله
للعلوم والتقنية
King Abdullah University of
Science and Technology

Water Desalination
and Reuse Center

Role of Environmental Biotechnology in Enabling Transition from Waste to Resource

Pascal E. Saikaly

Professor, Environmental Science and Engineering

AAEES Webinar Series

May 15, 2024

Waste to
Resource

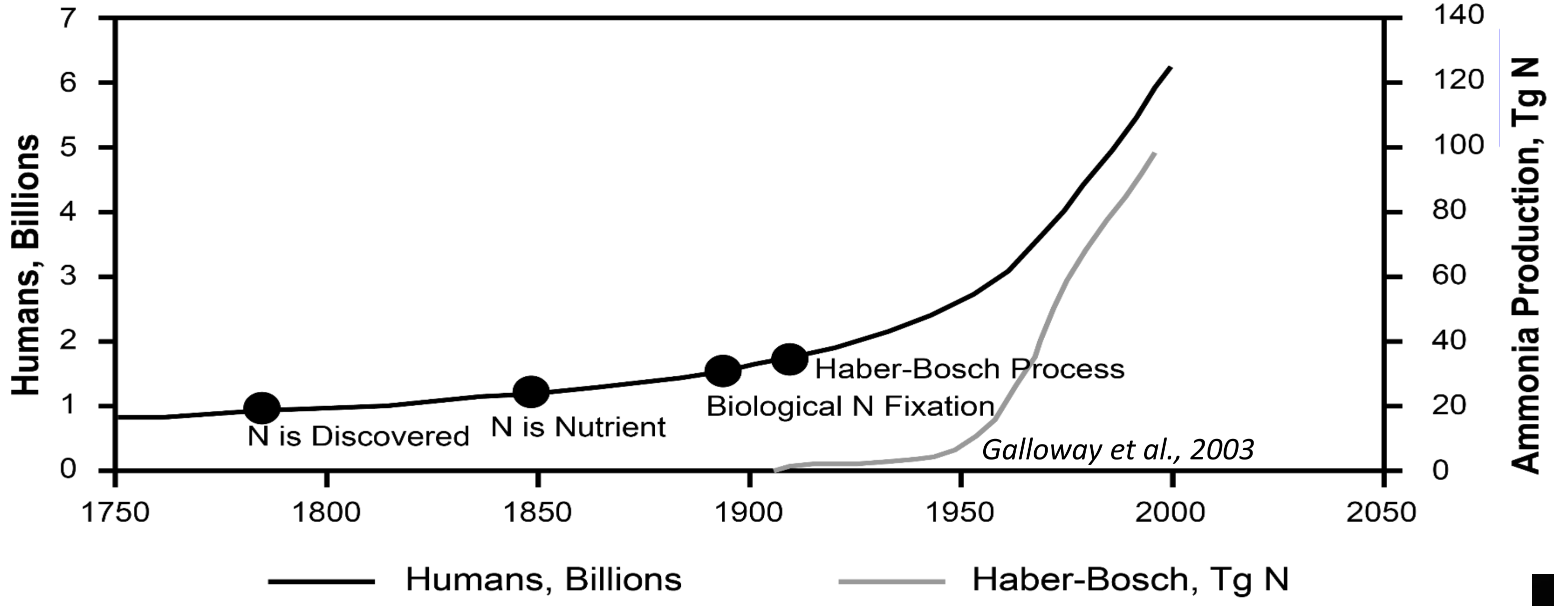
Haber-Bosch – 111 years old (1913)…generate pollutants

The Rellinghausen WWTP
First full-scale activated sludge treatment plant on the European continent

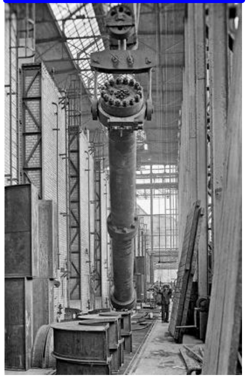
Edward Ardern

William Lockett

Haber-Bosch – 111 years old (1913)…generate pollutants

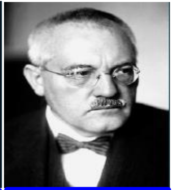


Haber-Bosch (1913)



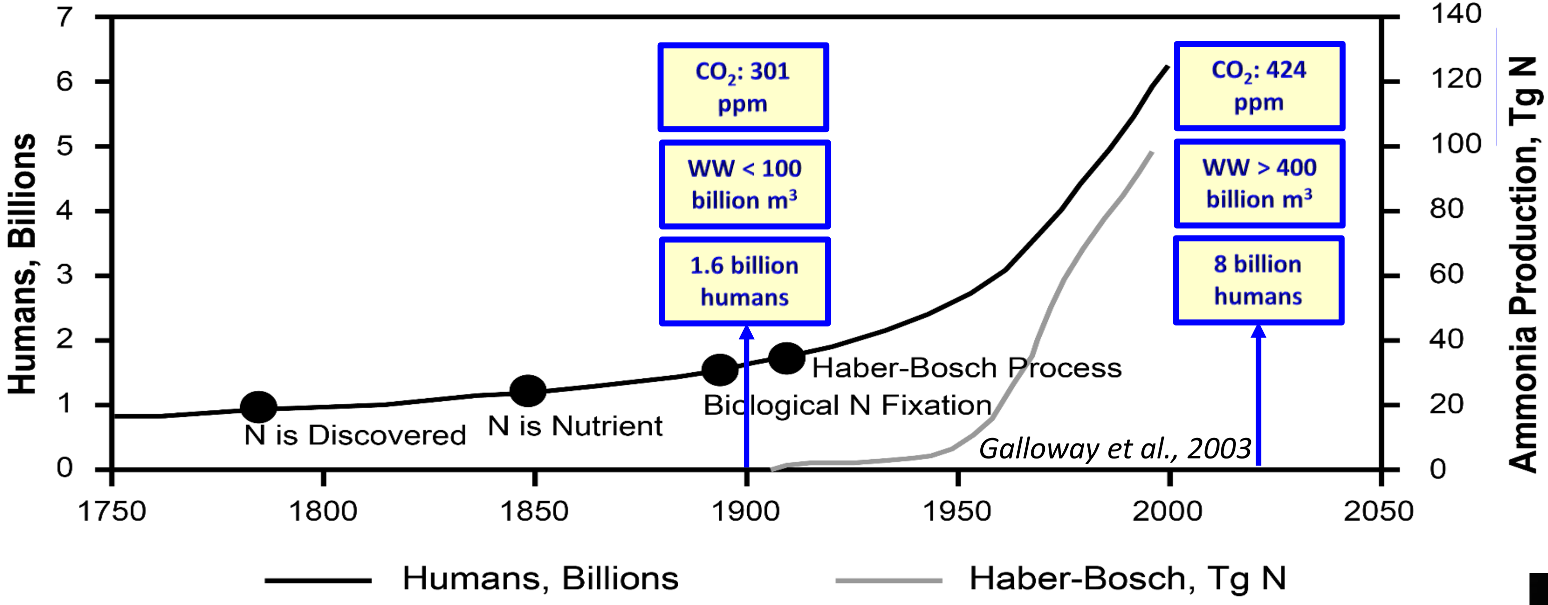
$3H_2 + N_2 \rightarrow 2NH_3$

Fritz Haber

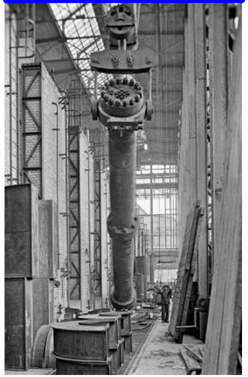


Carl Bosch

Haber-Bosch – 111 years old (1913)…generate pollutants

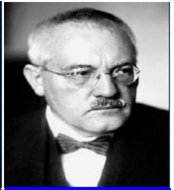


Haber-Bosch (1913)



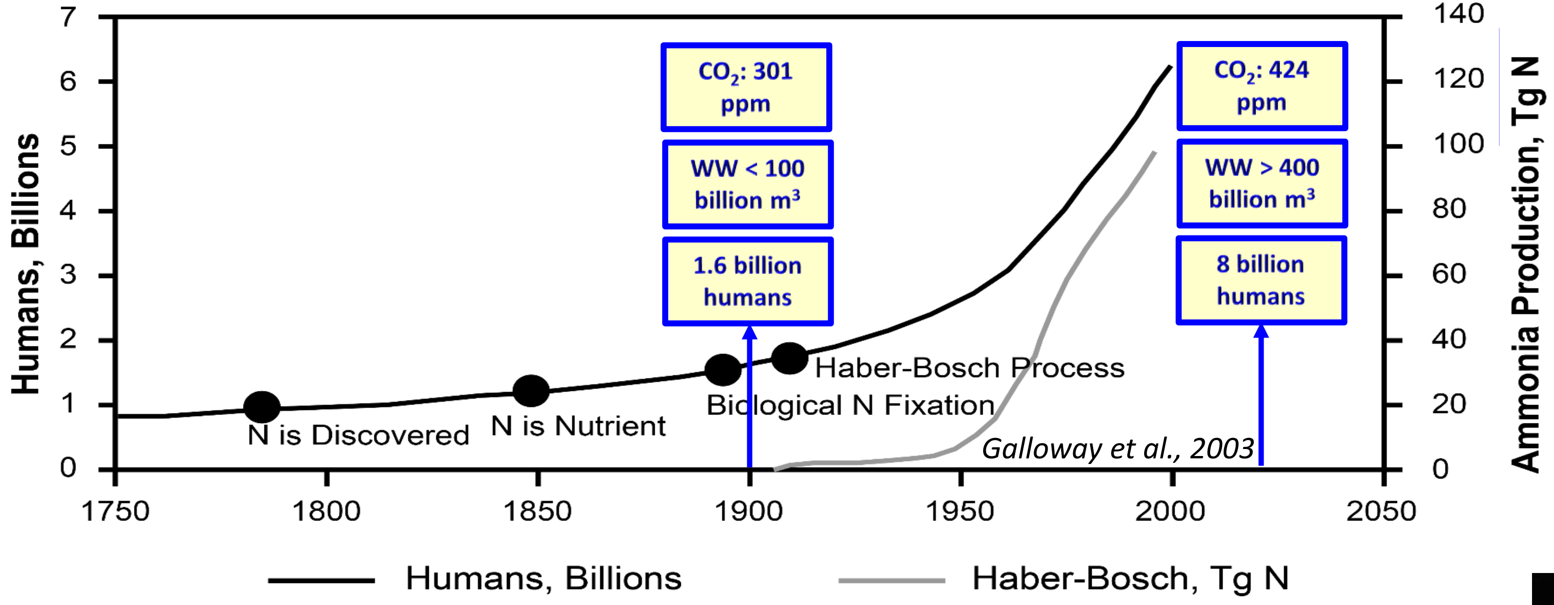
$$3H_2 + N_2 \rightarrow 2NH_3$$

Fritz Haber

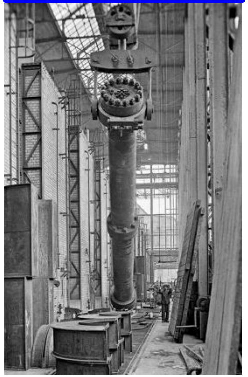


Carl Bosch

Haber-Bosch – 111 years old (1913)…generate pollutants

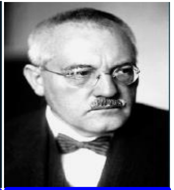


Haber-Bosch (1913)



$3H_2 + N_2 \rightarrow 2NH_3$

Fritz Haber

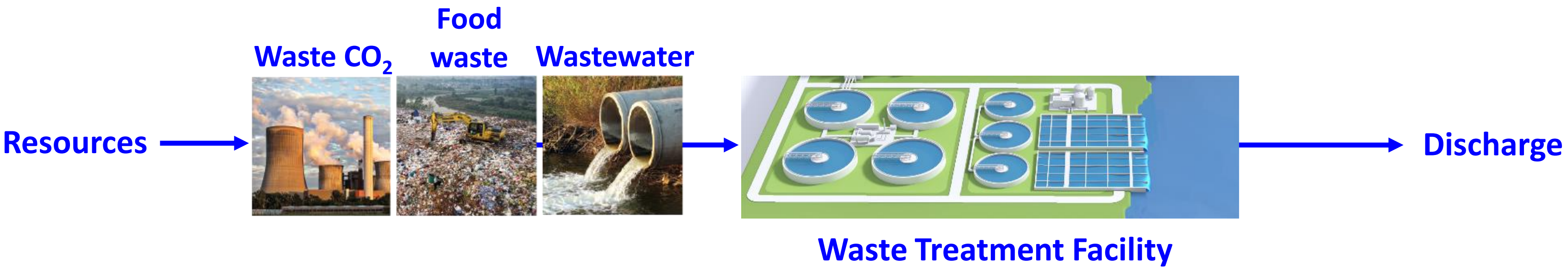


Carl Bosch

Haber-Bosch (150 million tons NH_3/year): 1500 TWh/year

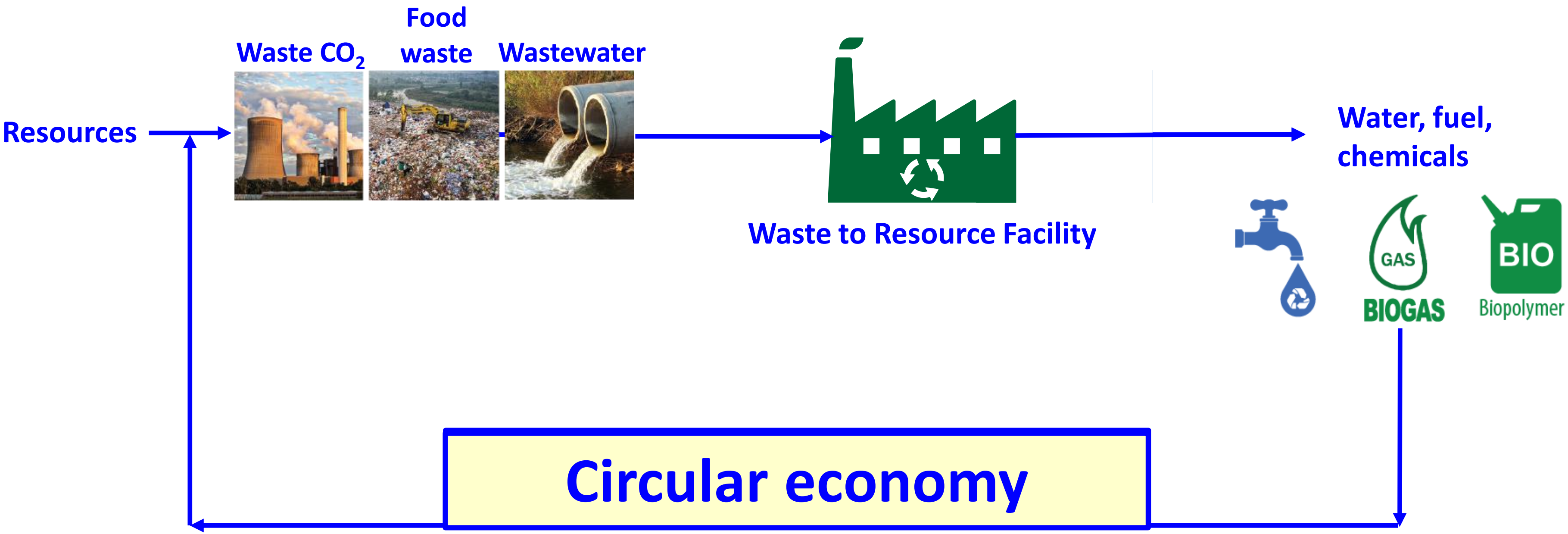
Wastewater treatment plants (20 million tons NH_3/year): $NH_3 \rightarrow N_2$ (150 TWh/year)

Paradigm shift in thinking: waste as a resource



Linear economy

Paradigm shift in thinking: waste as a resource



Wastewater treatment plants: treatment and disposal

Large footprint

0.6 kWh/m^3
(0.3 kWh/m^3 for aeration)
0.564 Kg CO_2e/m^3

Paradigm shift: From “Wastewater Treatment Plants” to “Resource Recovery Facilities”

Biopolymers

Large footprint

0.6 kWh/m^3
(0.3 kWh/m^3 for aeration)
0.564 Kg CO_2e/m^3

Chemical energy in biodegradable organics and NH_3 (1.54 kWh/m^3)

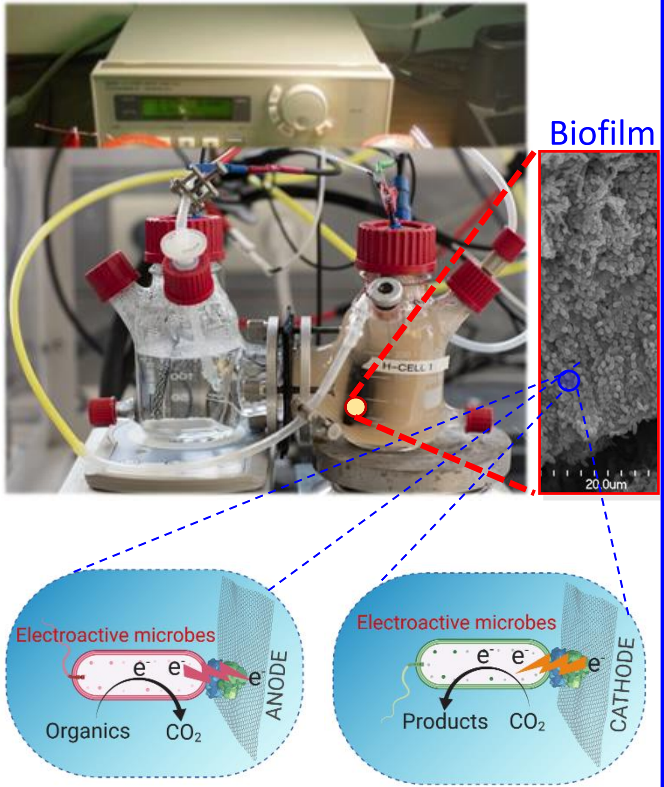
N, P

Safe water reuse: agriculture, industrial, residential, urban, aquifer recharge

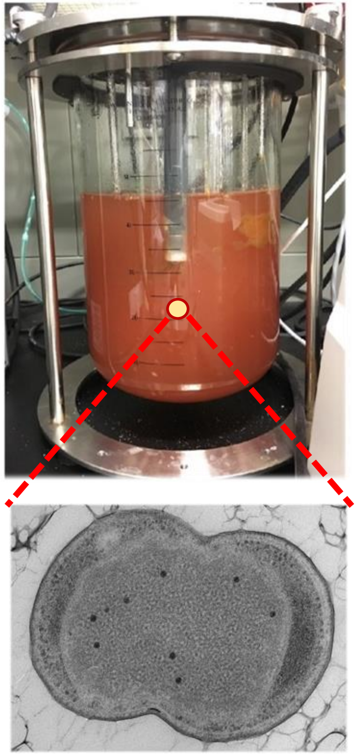
Drivers for developing next-generation environmental biotechnologies for achieving circular economy in WWT and reuse

Overarching goal - develop sustainable environmental biotechnologies that enable us to fully harness the metabolic potential of microbial communities for resource recovery from wastewater

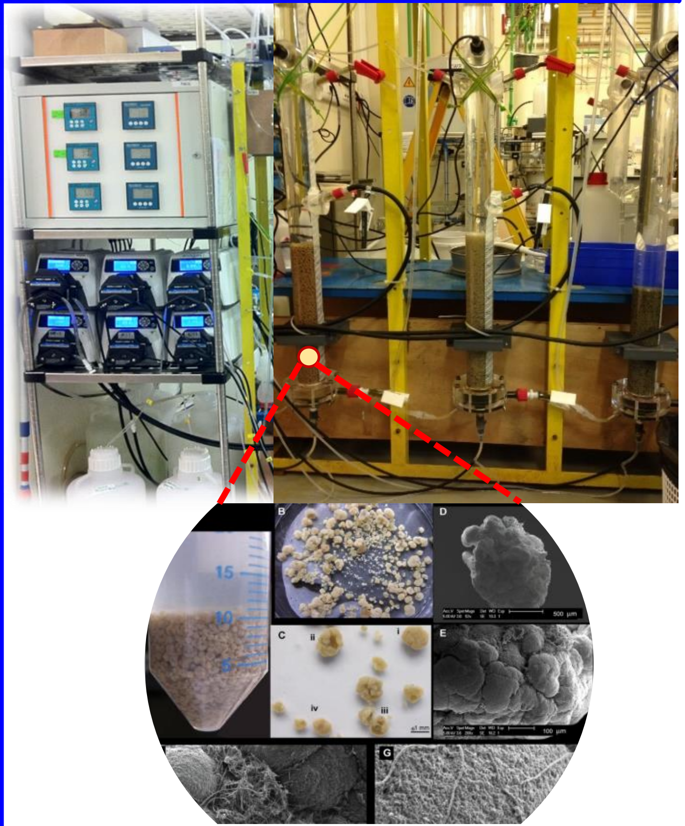
Microbial electrochemical systems	Anammox	Aerobic granular sludge



Electroactive microbes

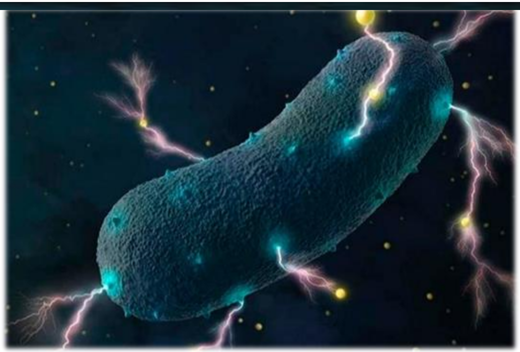


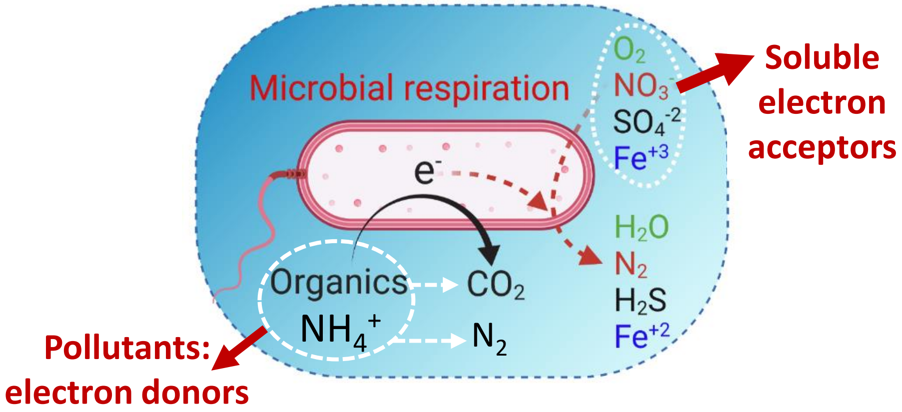
Anaerobic ammonia oxidizing bacteria



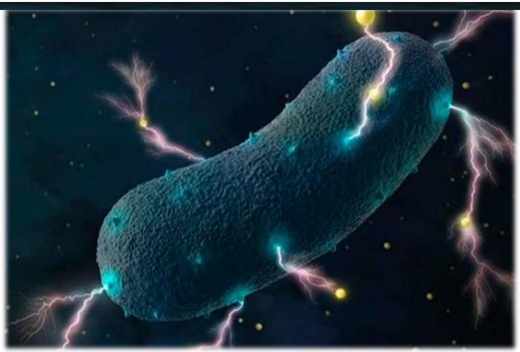
Bacteria aggregating as granules

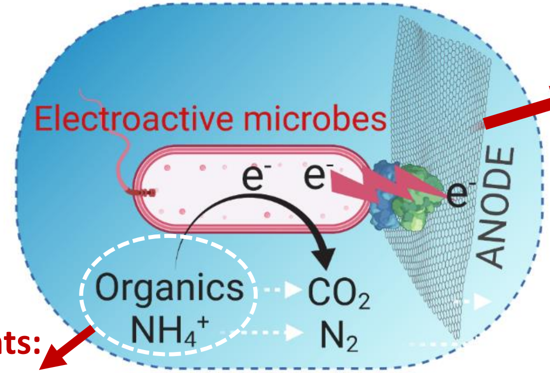
1. Microbial electrochemical systems





1. Microbial electrochemical systems

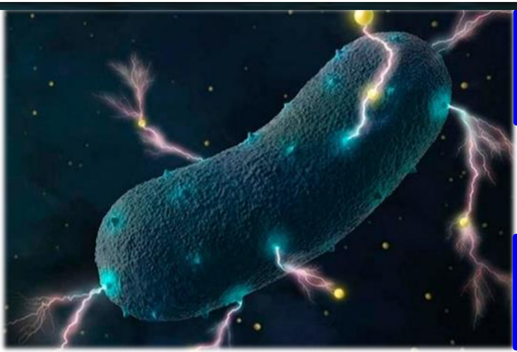




“Breath” solid-state electron acceptors

Pollutants: electron donors

1. Microbial electrochemical systems

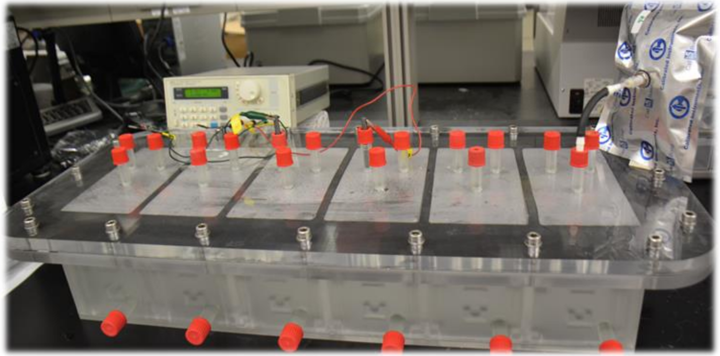


Theme 1: Microbial electrolysis cell for achieving energy-neutral domestic wastewater treatment and reuse

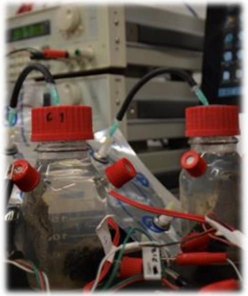
Theme 2: Microbial electrosynthesis for converting CO_2 to chemicals and fuels

1.0 L

15.0 L

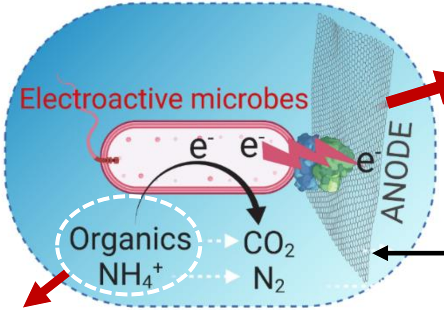


0.3 L



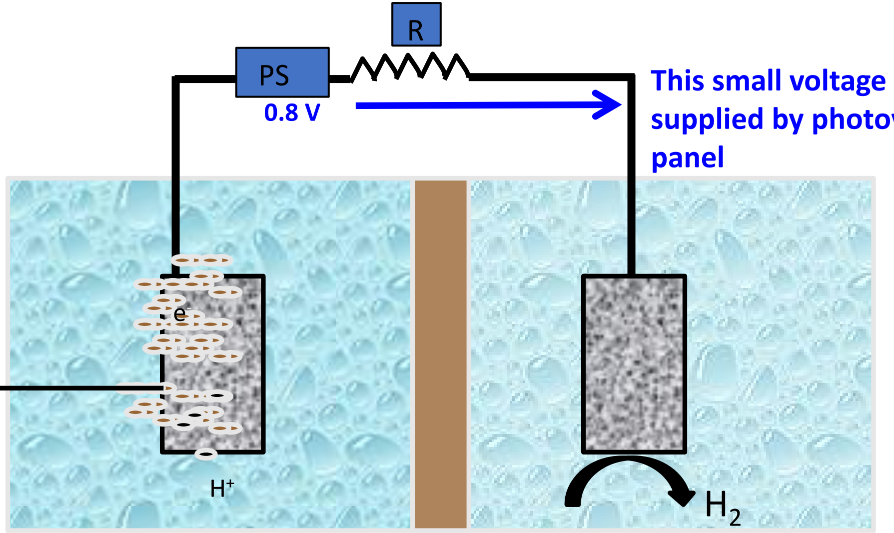
Lab- and pilot-scale

Theme 1: Microbial electrolysis cell for WWT with resource recovery



"Breath" solid-state electron acceptors

Pollutants: electron donors



This small voltage can be supplied by photovoltaic solar panel

Anode (Anaerobic)

Membrane

Cathode (Anaerobic)

Anodic chamber (Anaerobic)

$$CH_3COO^- + 4H_2O \rightarrow 2HCO_3^- + 9H^+ + 8e^-$$

$E° = - 0.28$ V

Cathodic chamber (Anaerobic)

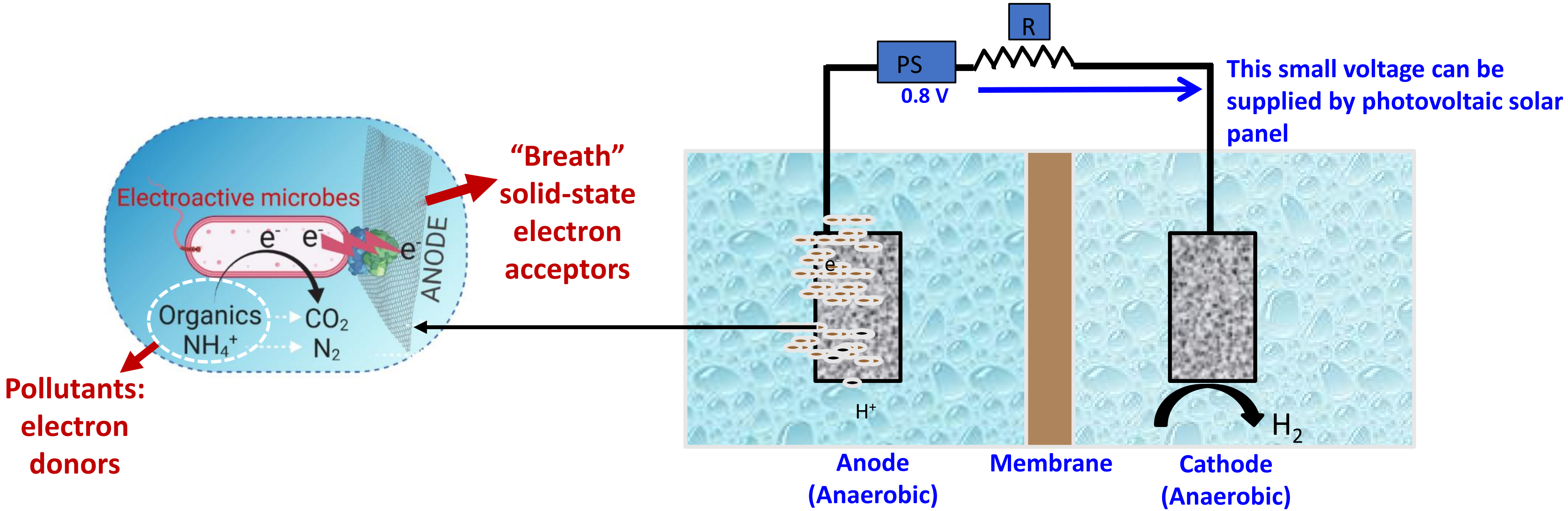
$$2H^+ + 2e^- \rightarrow H_2$$

$E° = - 0.41$ V

$E_{eq} = - 0.13$ V

Theme 1: Microbial electrolysis cell for WWT with resource recovery

MEC alone are not able to produce the high-quality effluent needed for water reuse applications



Anodic chamber (Anaerobic)

$$CH_3COO^- + 4H_2O \rightarrow 2HCO_3^- + 9H^+ + 8e^-$$ $E° = -0.28$ V

Cathodic chamber (Anaerobic)

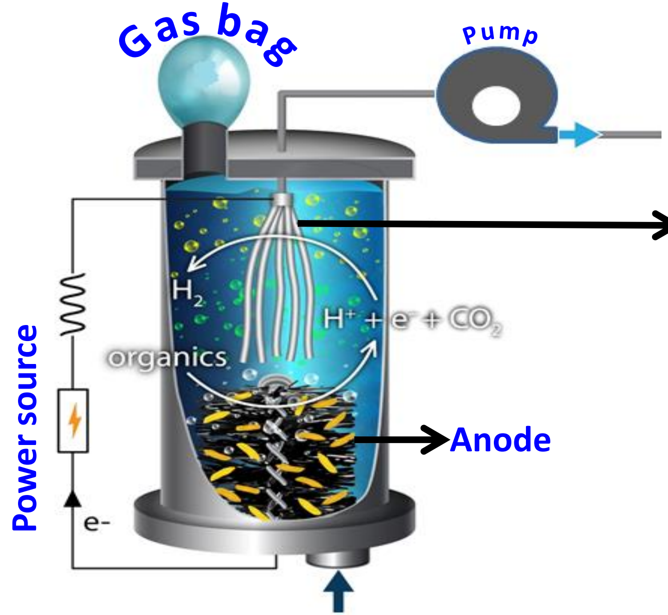
$$2H^+ + 2e^- \rightarrow H_2$$ $E° = -0.41$ V

$E_{eq} = -0.13$ V

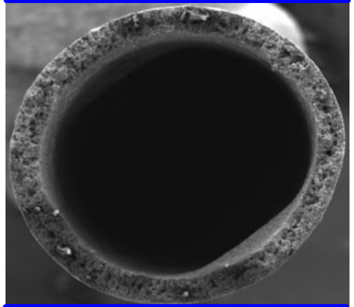
Dr. Krishna Katuri

Anaerobic electrochemical membrane bioreactor (AnEMBR)

Simultaneous recovery of energy (H_2) and water for reuse from wastewater



Dual function cathode



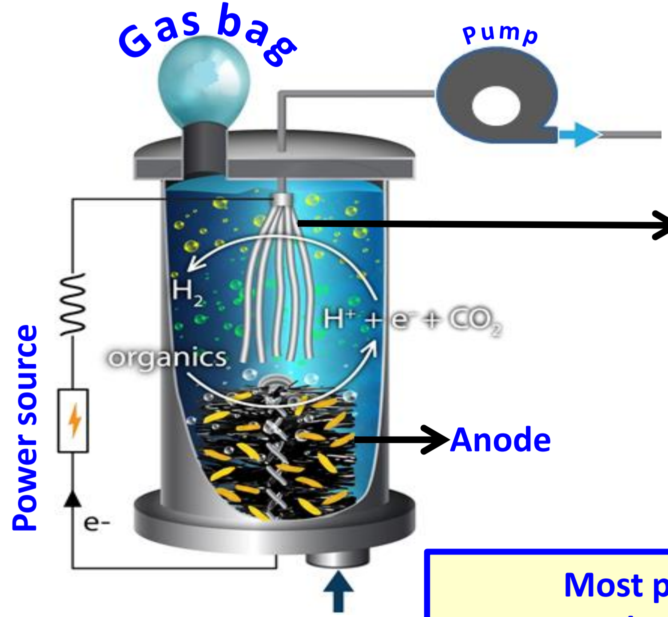
Electro-catalytic & porous polyemric HFM

Current Opinion in Biotechnology, 2019, 57,101-110; *Journal of Membrane Science*, 2019, 577, 176-183; *Environmental Science and Technology*, 2016, 50, 4439-4447; *Advanced Materials*, 2016 , 28, 9504-9511; **Patent: WO 2015/103590 A1**

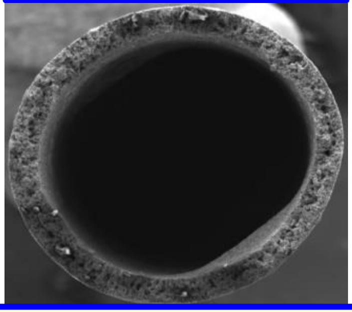
Dr. Krishna Katuri

Anaerobic electrochemical membrane bioreactor (AnEMBR)

Simultaneous recovery of energy (H_2) and water for reuse from wastewater



Dual function cathode



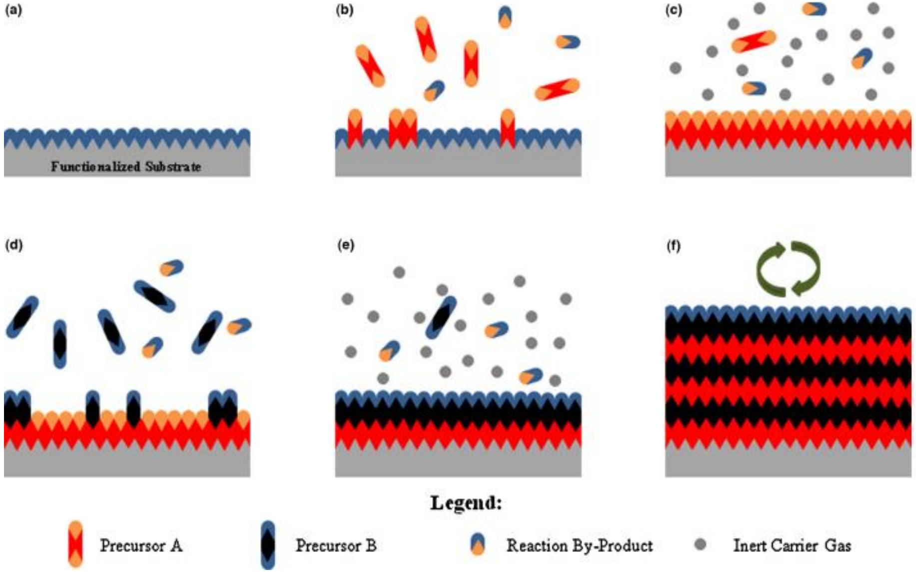
Most polymers are electric insulators
How to make HF polymeric membranes conductive and catalytic?

Current Opinion in Biotechnology, 2019, 57,101-110; *Journal of Membrane Science*, 2019, 577, 176-183; *Environmental Science and Technology*, 2016, 50, 4439-4447; *Advanced Materials*, 2016 , 28, 9504-9511; **Patent: WO 2015/103590 A1**

Fabrication of electro-catalytic polymer-based hollow fiber membrane (HFM) using atomic layer deposition

Dr. Krishna Katuri

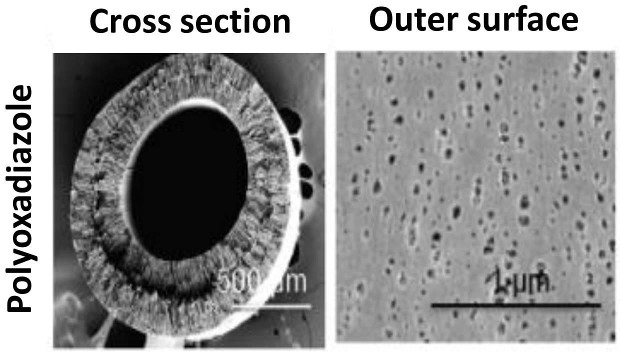
Atomic Layer Deposition



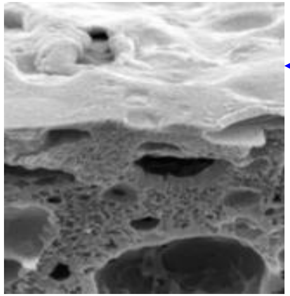
Johnson et al. (2014)

- **Allows control of film thickness**
- **Enables deposition of uniform films on the surface of substrates with porous structures**

Polymeric HFM

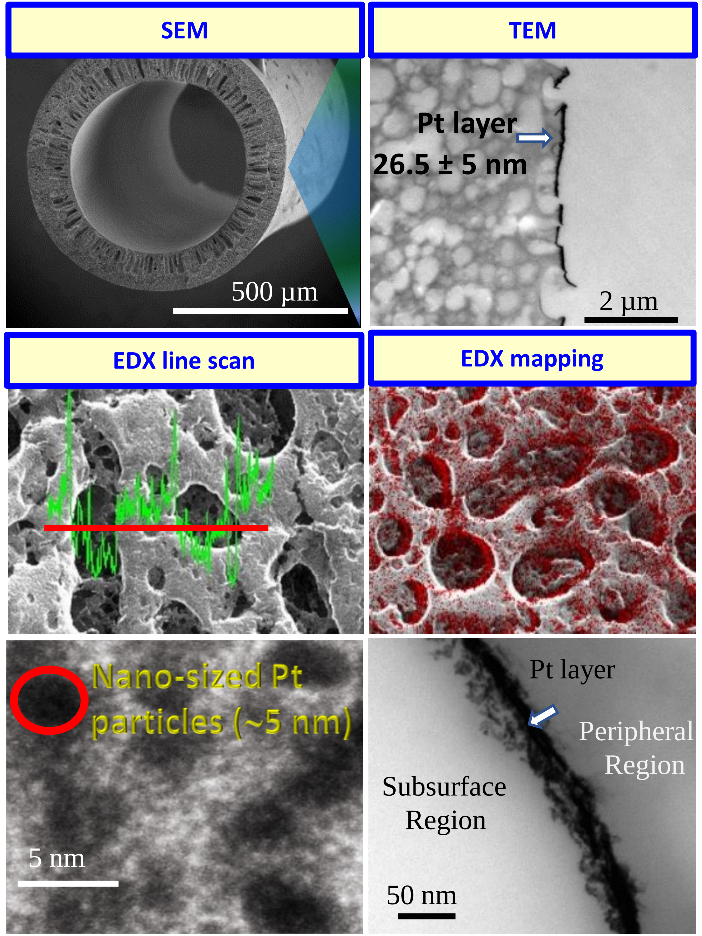


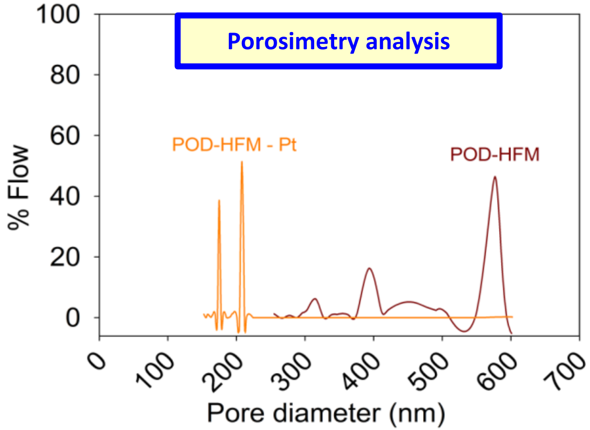
Thermally stable (up to 300°C)



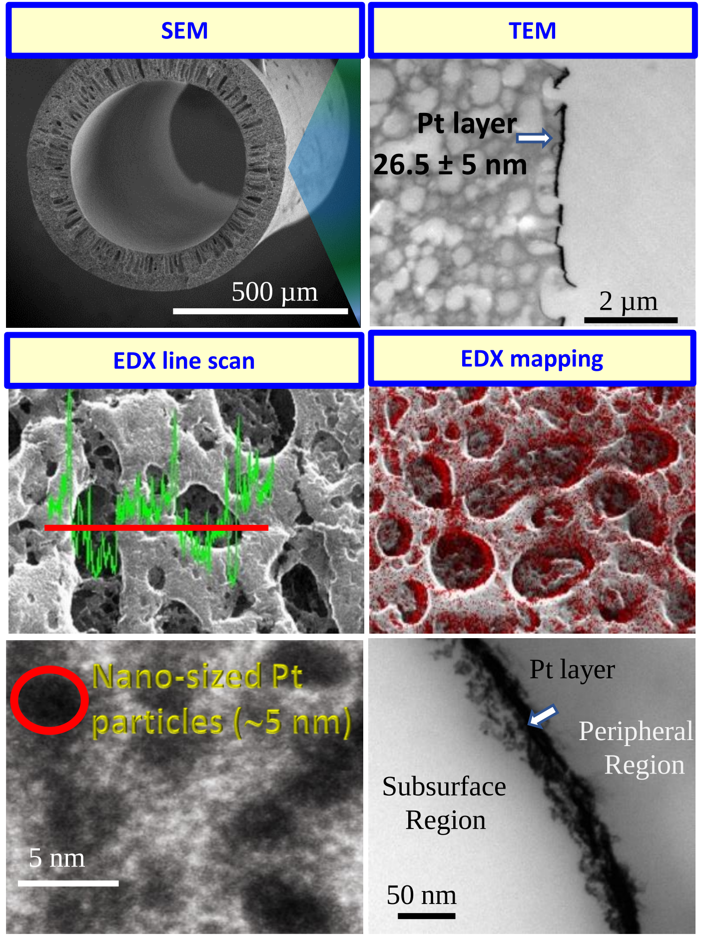
Pt layer

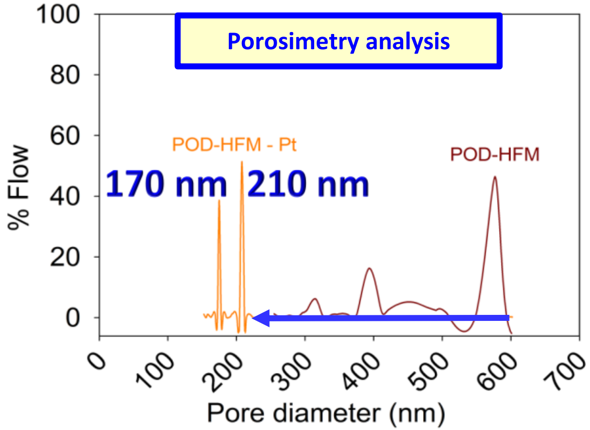
Electro-catalytic polymer-based HFM



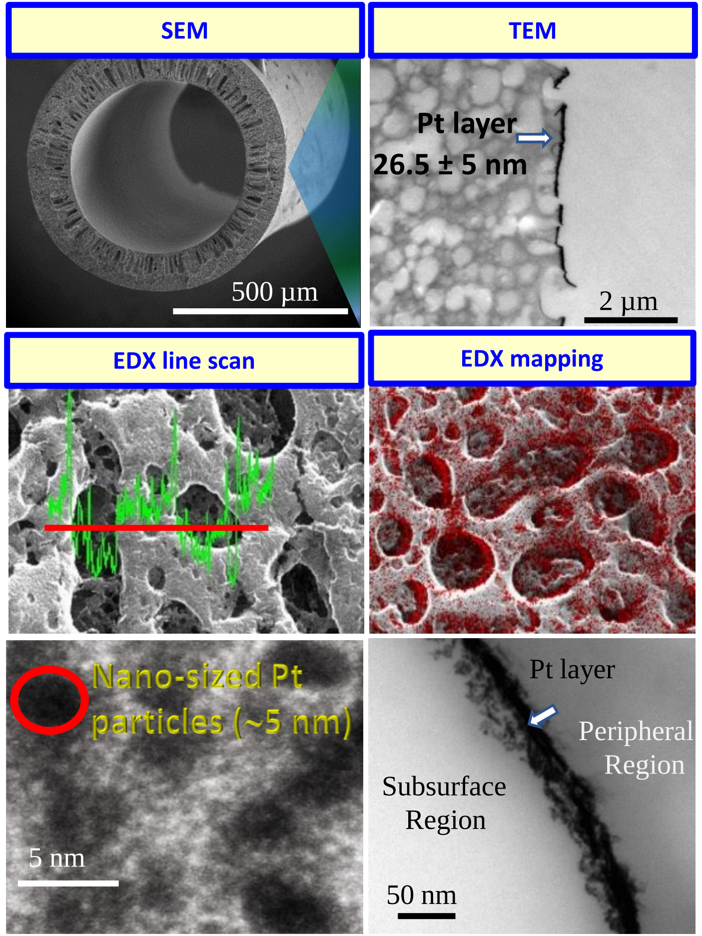


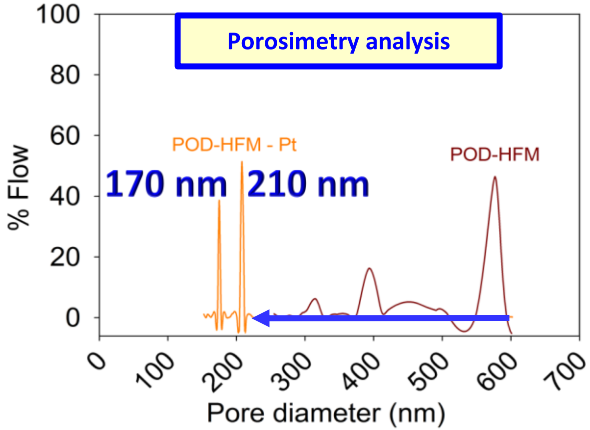
Electro-catalytic polymer-based HFM

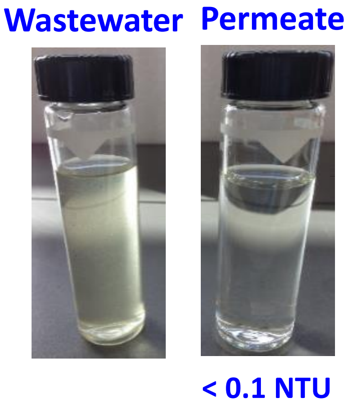




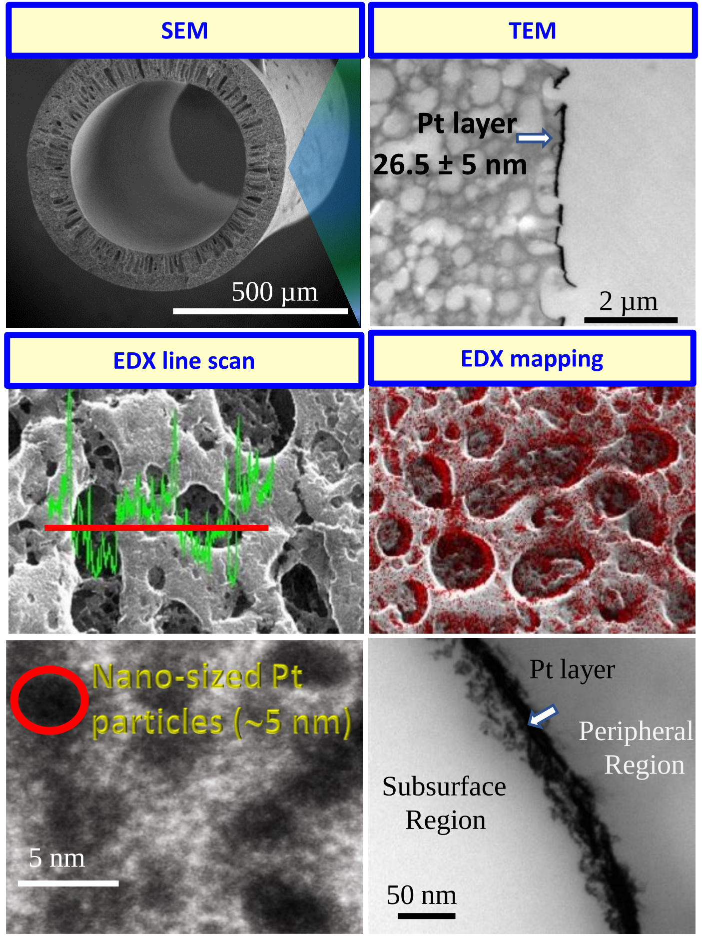
Electro-catalytic polymer-based HFM

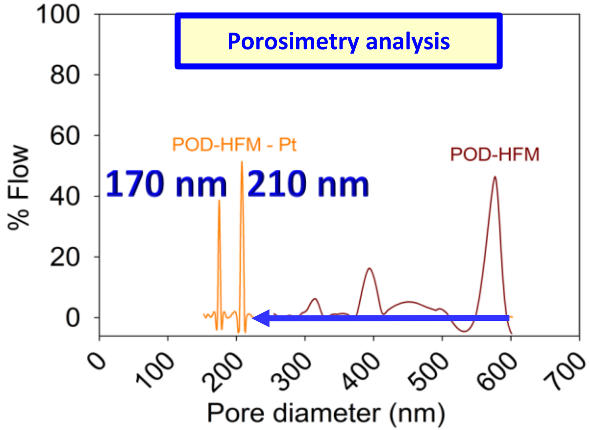


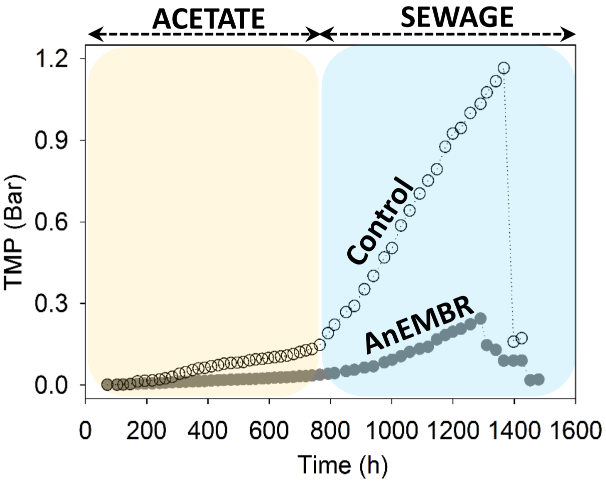


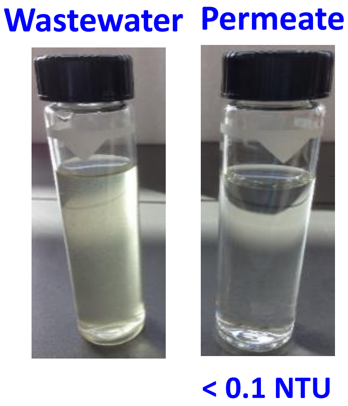


Electro-catalytic polymer-based HFM

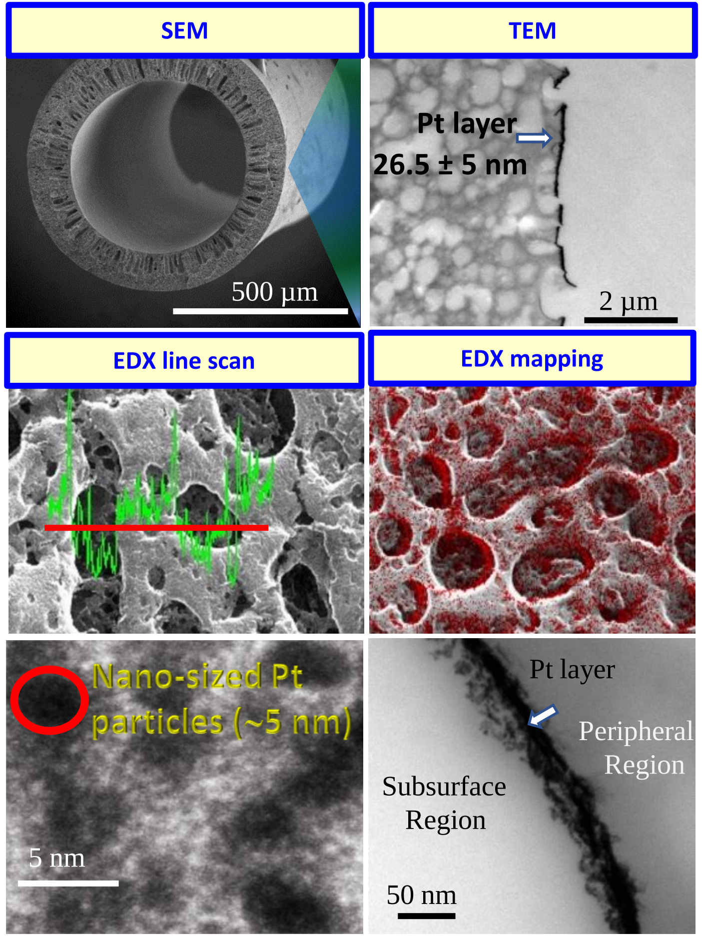


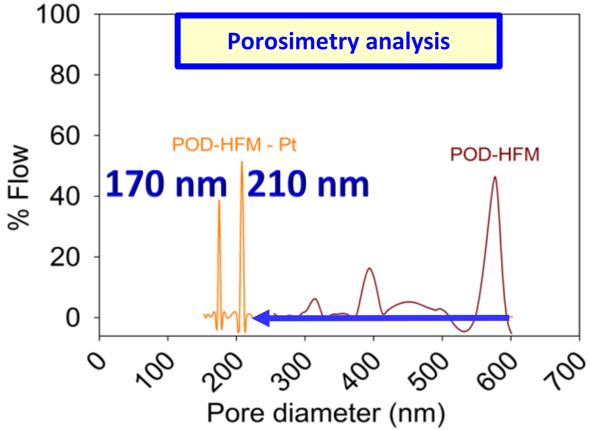


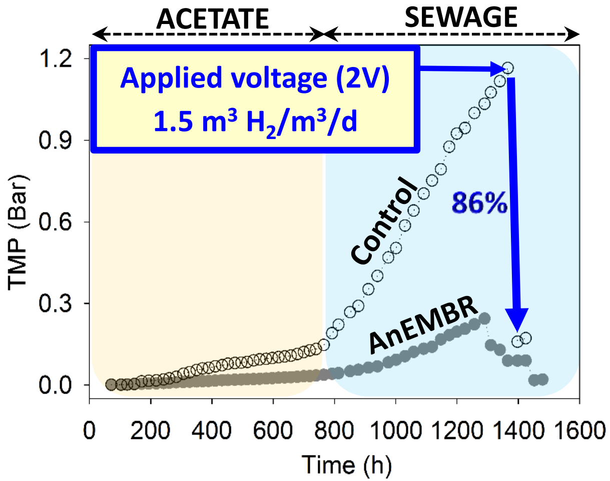


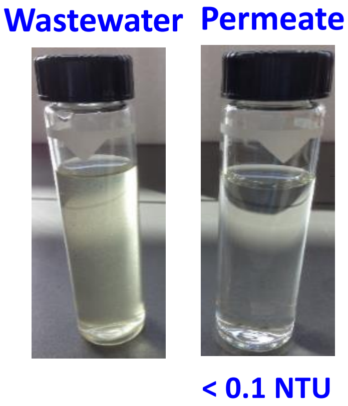


Electro-catalytic polymer-based HFM

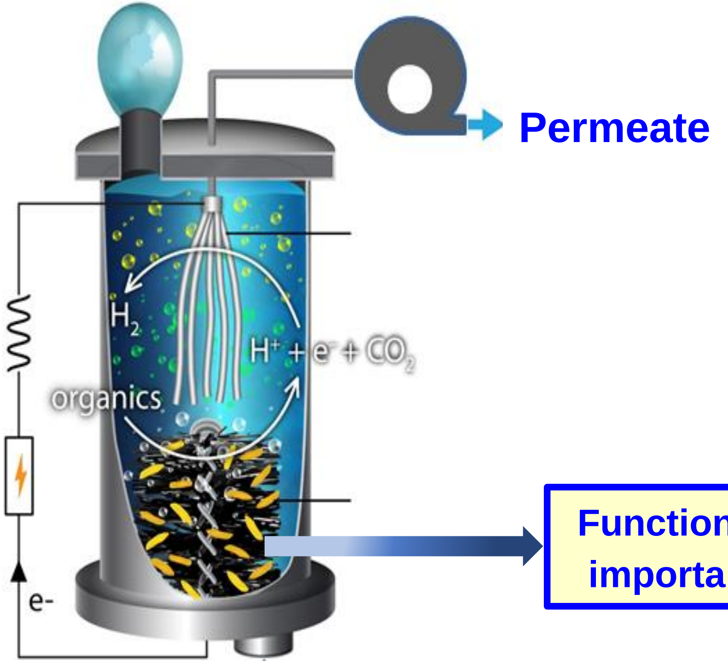






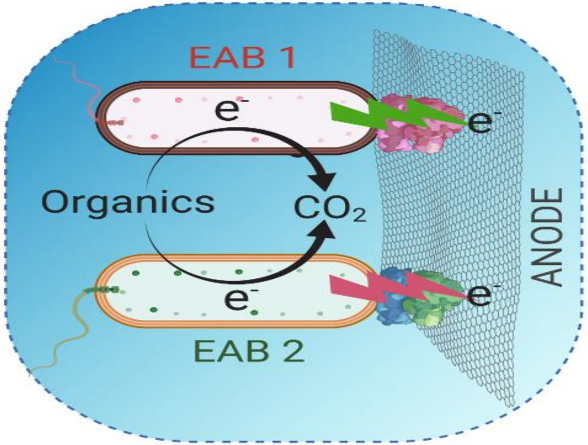


What about functional stability in terms of current density?

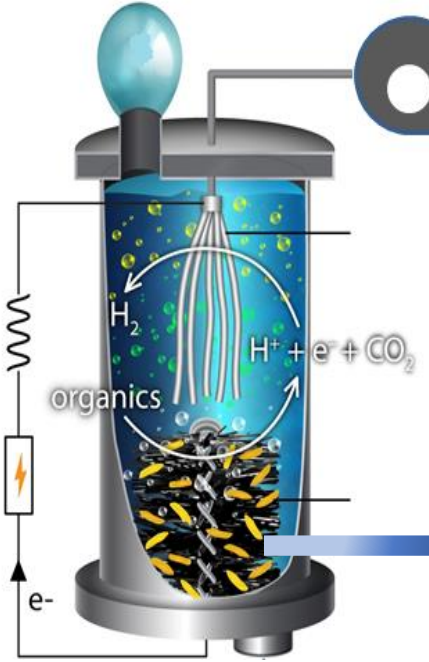


Wastewater (Organics, N, P)

Functional redundancy in EAB: important to maintain stability



What about functional stability in terms of current density?

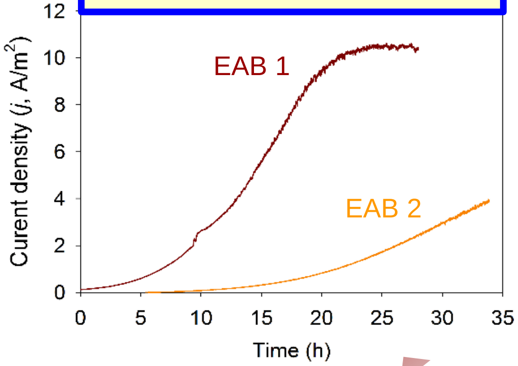


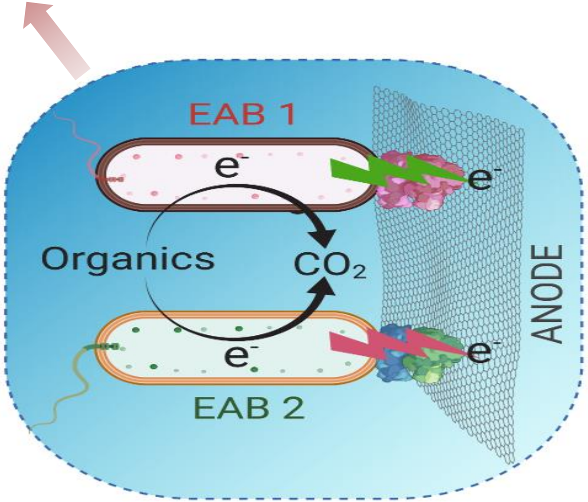
Permeate

Wastewater (Organics, N, P)

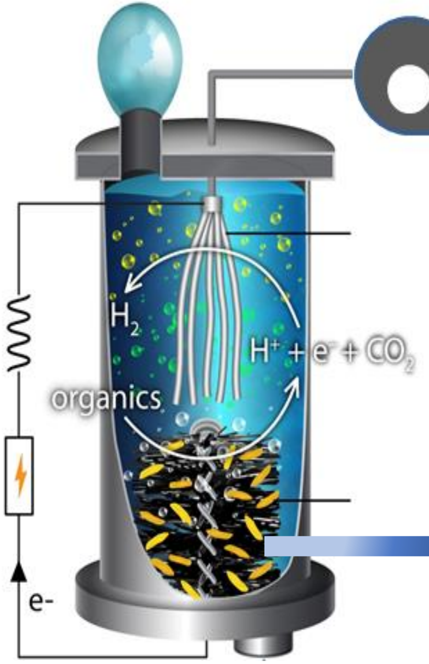
Functional redundancy in EAB: important to maintain stability

Poor functional redundancy

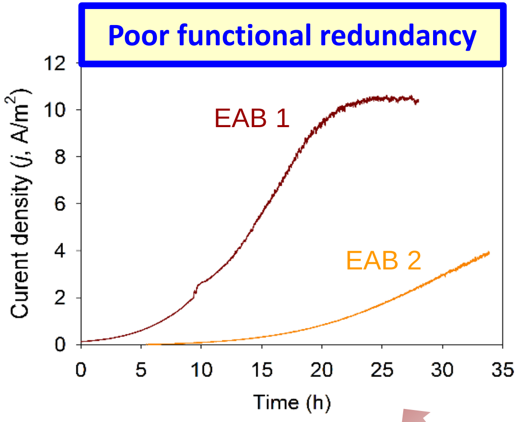


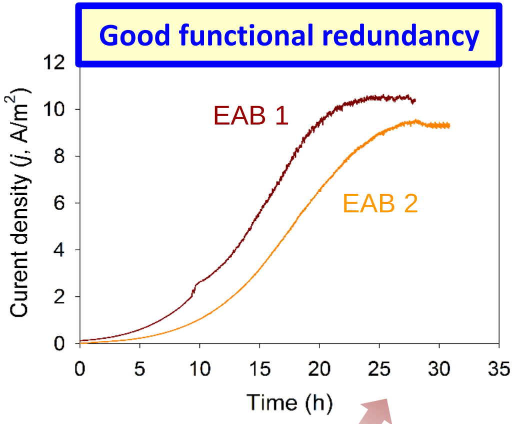


What about functional stability in terms of current density?

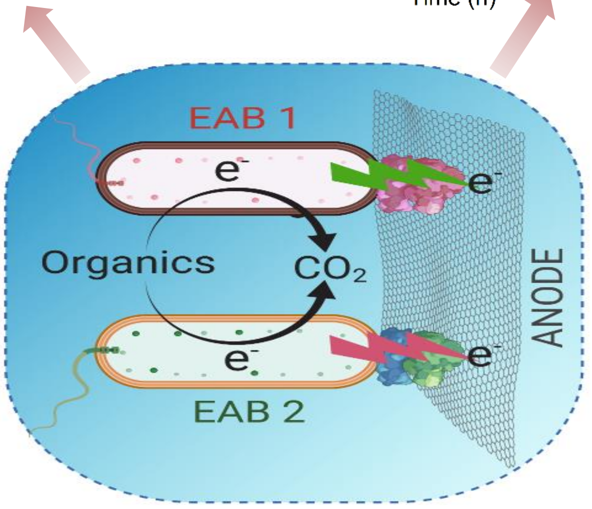


Permeate





Functional redundancy in EAB: important to maintain stability

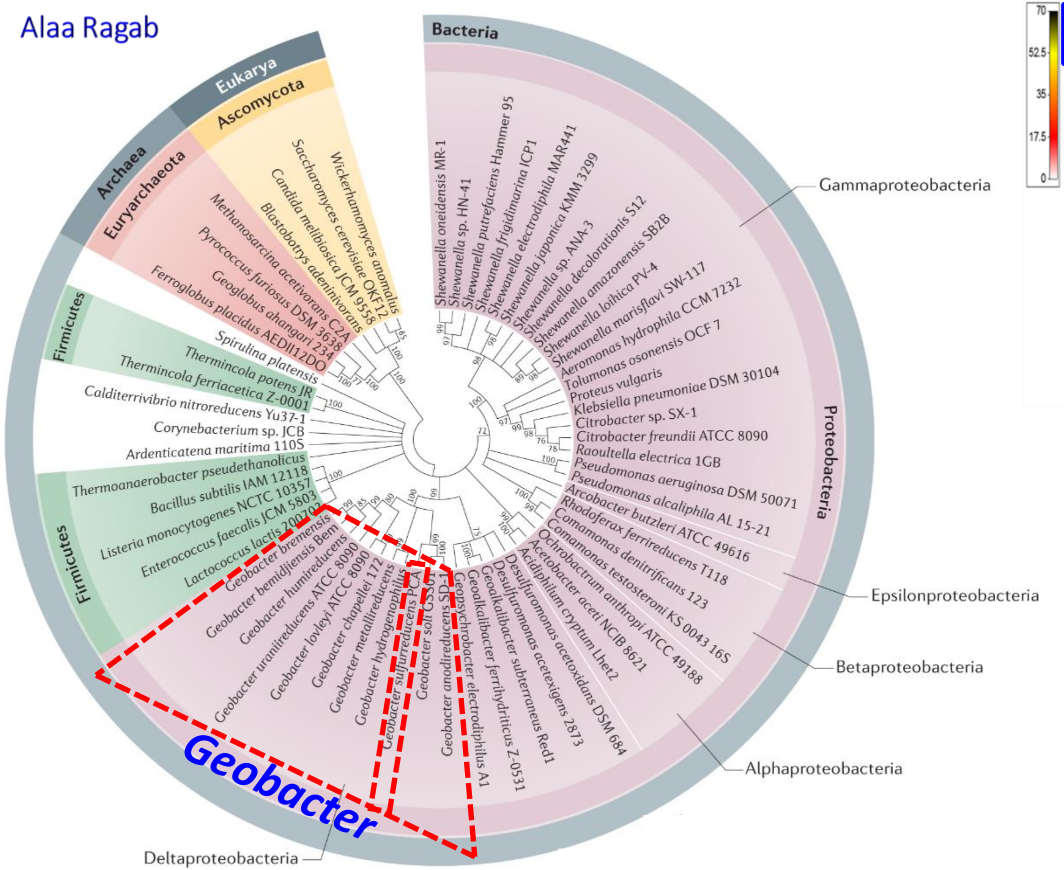


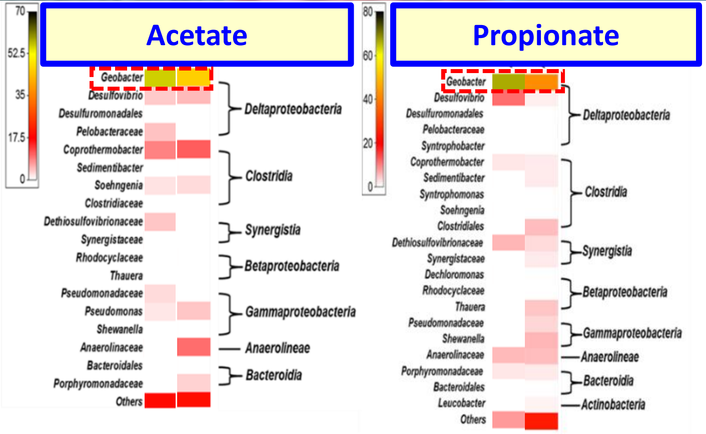
Wastewater (Organics, N, P)

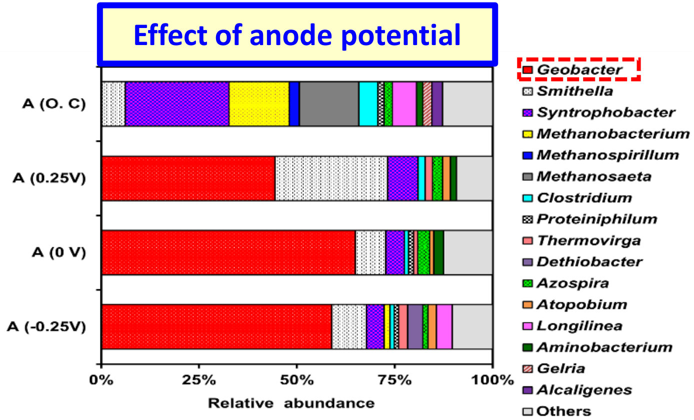
Diversity of electroactive microbes/dominance of *Geobacter*

Alaa Ragab

Hari Anadarao





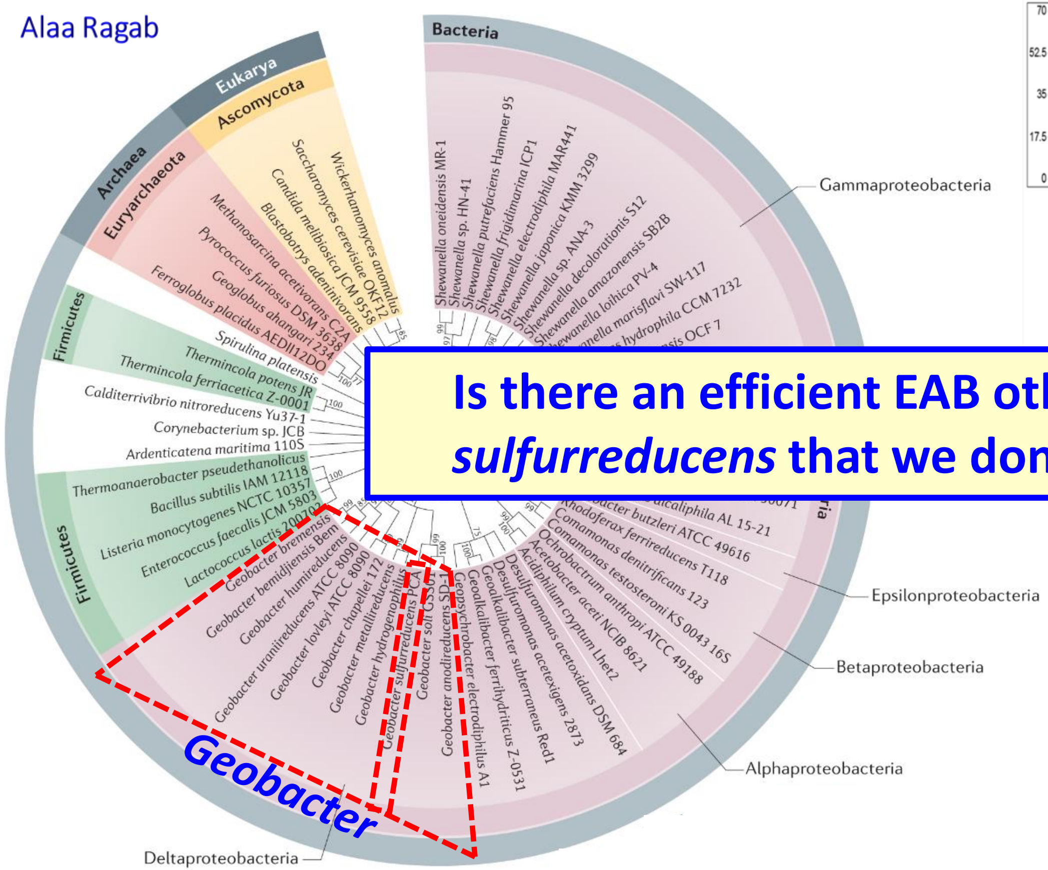


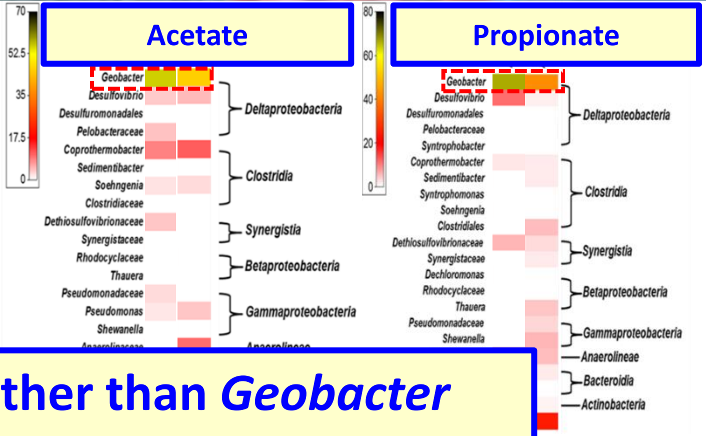
Nature Reviews Microbiology, 2019, 17, 307-319; *Frontiers in Microbiology*, 2017, 8:1371; *Scientific Reports*, 2016, 6:38690; *Applied Microbiology and Biotechnology*, 2016, 100, 5999-6011

Diversity of electroactive microbes/dominance of *Geobacter*

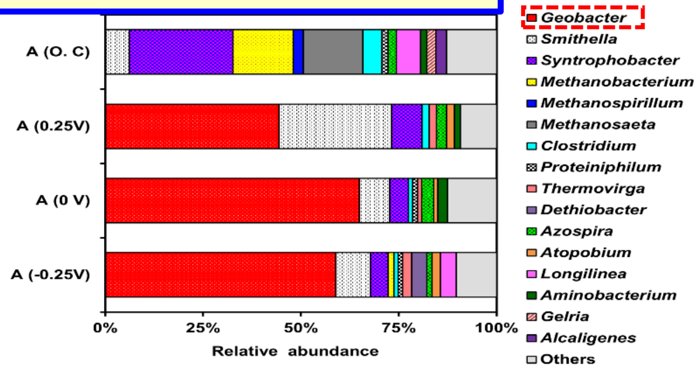
Alaa Ragab

Hari Anadarao





Is there an efficient EAB other than *Geobacter sulfurreducens* that we don't know about yet?

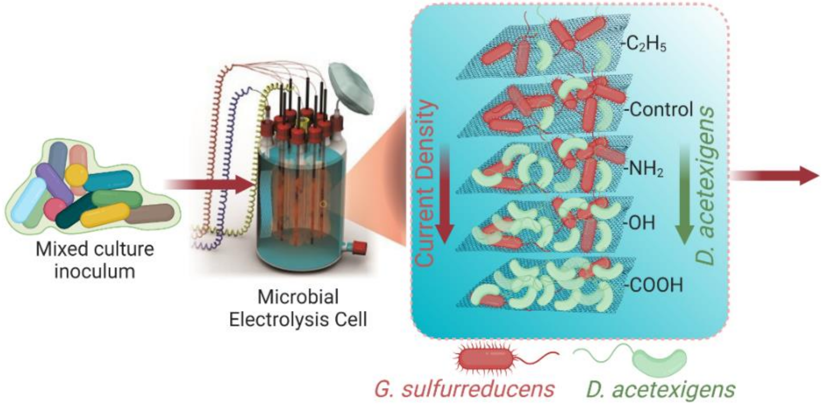


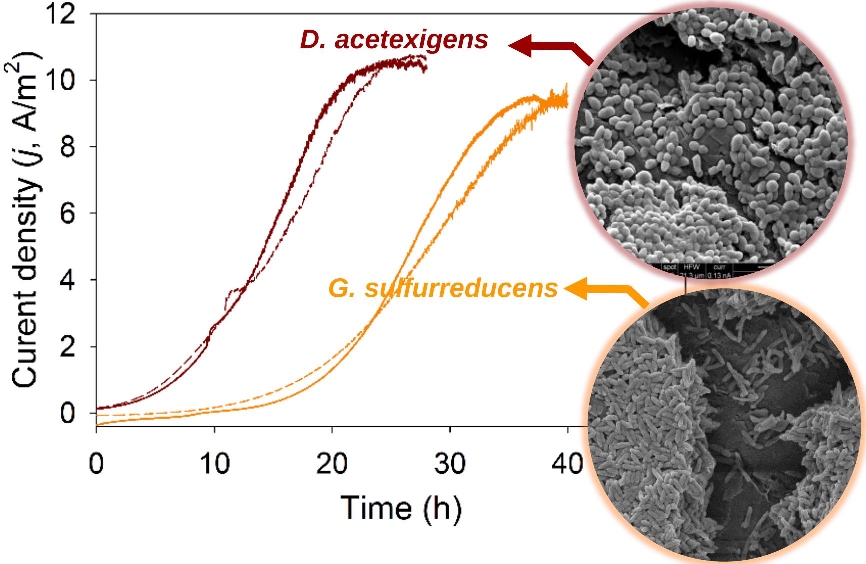
Nature Reviews Microbiology, 2019, 17, 307-319; *Frontiers in Microbiology*, 2017, 8:1371; *Scientific Reports*, 2016, 6:38690; *Applied Microbiology and Biotechnology*, 2016, 100, 5999-6011

Desulforomonas acetexigens: an efficient EAB

Dr. Krishna Katuri

Dr. Veerraghavulu Sapireddy



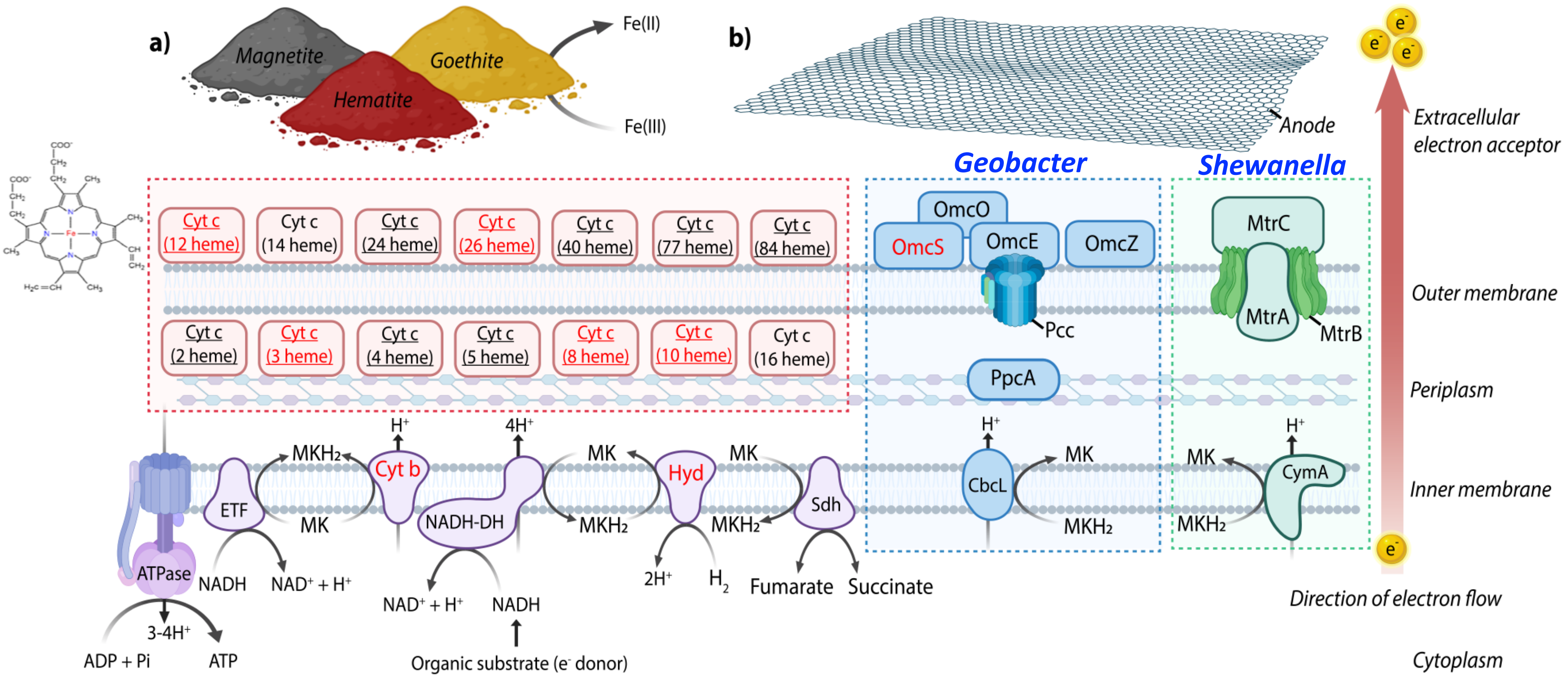


Npj Biofilms and Microbiomes, 2021, 7:47; *Water Research*, 2020, 185, 116284; *Genome Announcements*, 2017, 5(9):e01522-16

Extracellular electron transfer complexes in *D. acetexigens* revealed by differential proteomics

Dario Rangel Shaw

Dr. Krishna Katuri

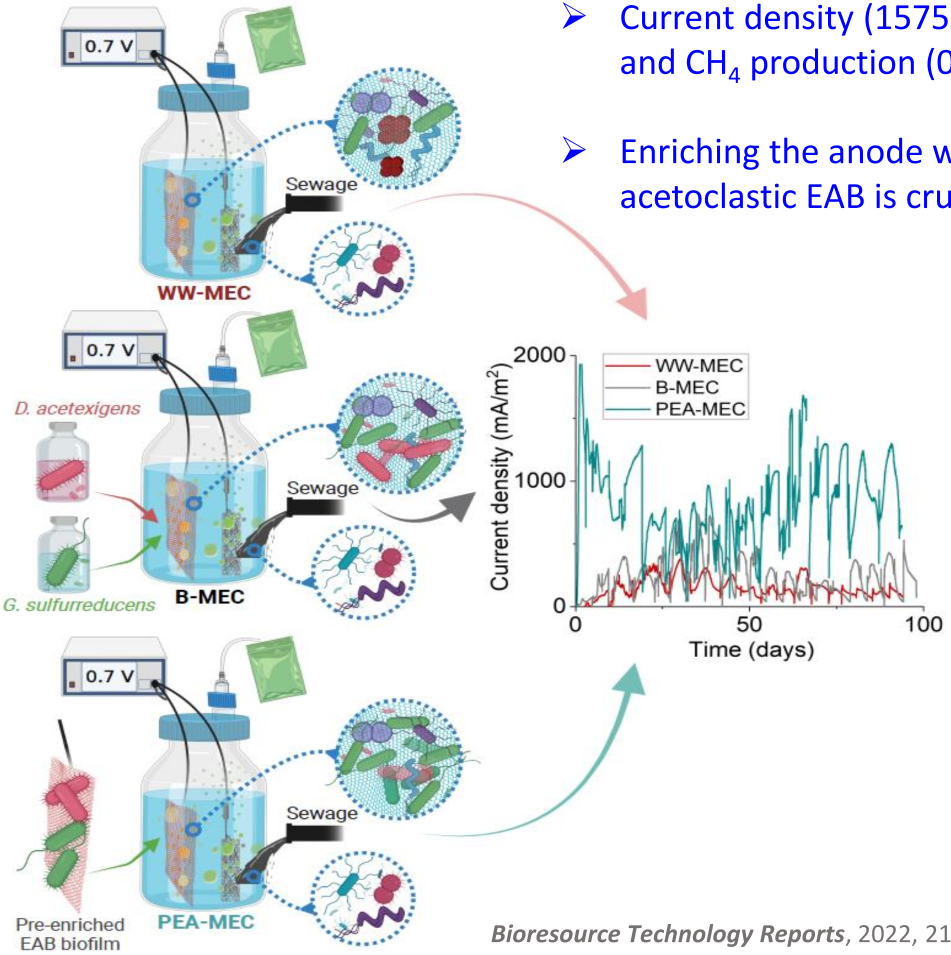


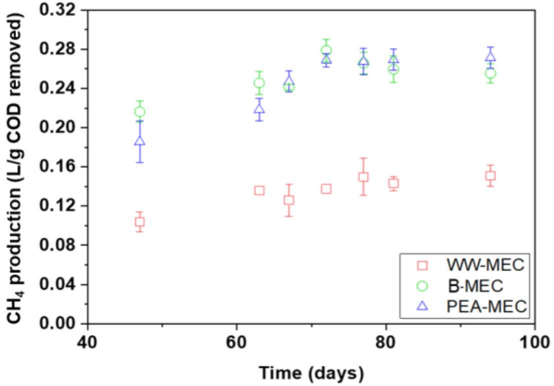
Manuscript in preparation

Mohammed Bader

Effect of different start-up strategies on the enrichment of efficient acetoclastic electroactive bacteria (i.e., *G. sulfurreducens and D. acetexigens)*

- Current density (1575 ± 157 mA/m^2), coulombic efficiency (70.3 ± 9%), and CH_4 production (0.27±0.02 L/g-COD) was highest in PEA-MECs
- Enriching the anode with functionally redundant and efficient acetoclastic EAB is crucial for resource recovery from wastewater



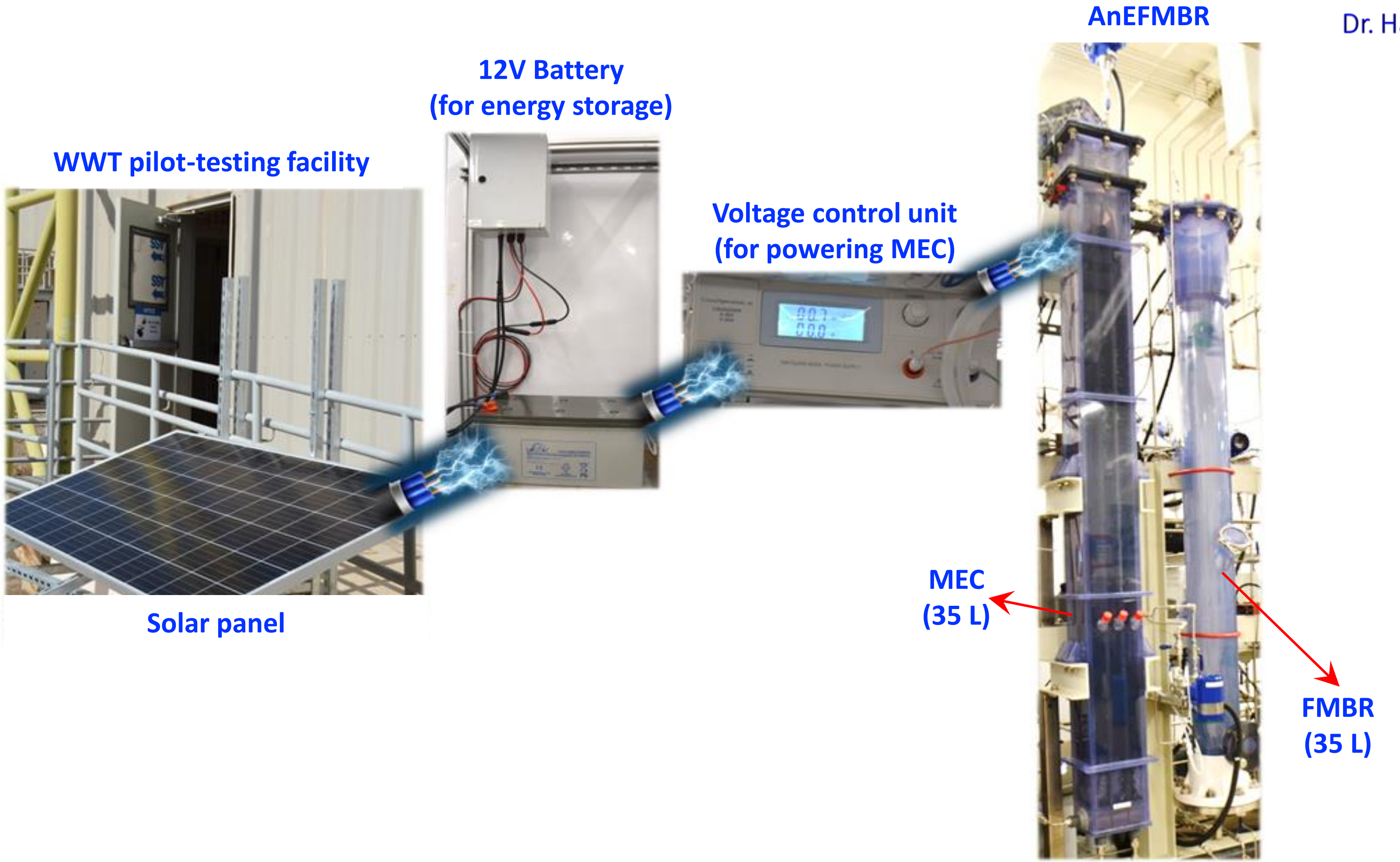


Bioresource Technology Reports, 2022, 21, 101323

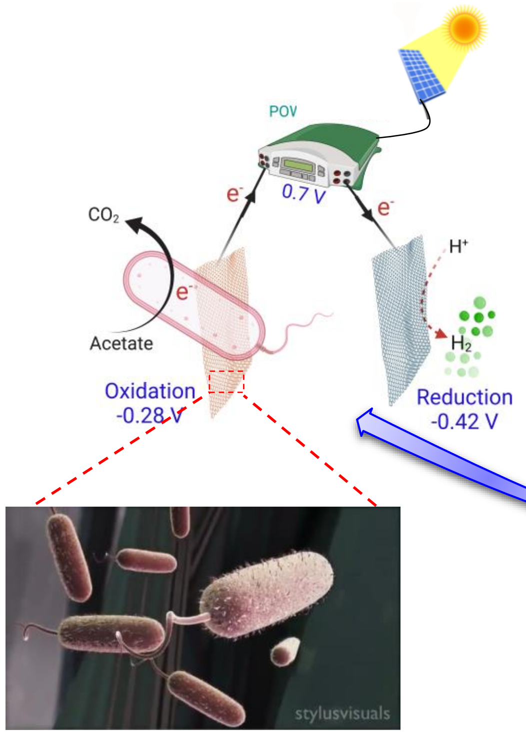
Pilot-scale anaerobic electrochemical fluidized membrane bioreactor for achieving energy-neutral WWT for non-potable reuse

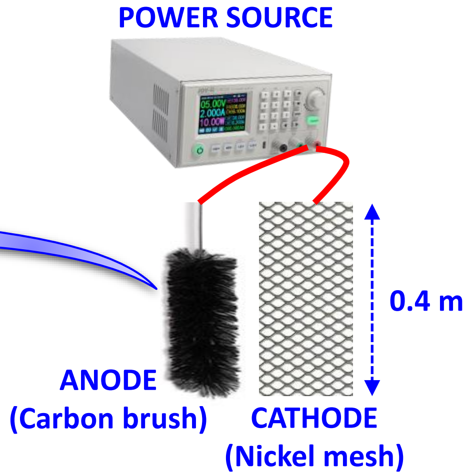
Dr. Krishna Katuri

Dr. Hari Anadarao



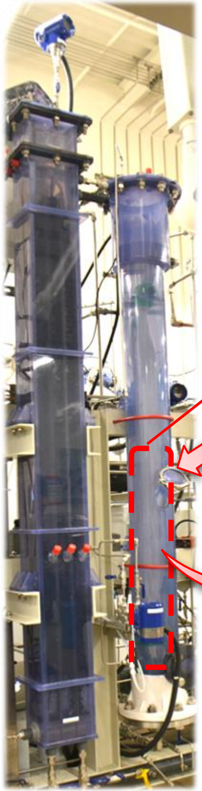
Pilot-scale anaerobic electrochemical fluidized membrane bioreactor for achieving energy-neutral WWT for non-potable reuse





- **Single chamber MEC**
- **Reactor working volume → 35 L**
- **Anode & cathode modules → 4**
- **Anode-to-volume ratio / module → 780 m^2/m^3**
- **Each module is powered separately**
- **Applied voltage → 1.0 V**
- **Inoculum: *G. sulfurreducens and D. acetexigens***

Pilot-scale anaerobic electrochemical fluidized membrane bioreactor for achieving energy-neutral WWT for non-potable reuse

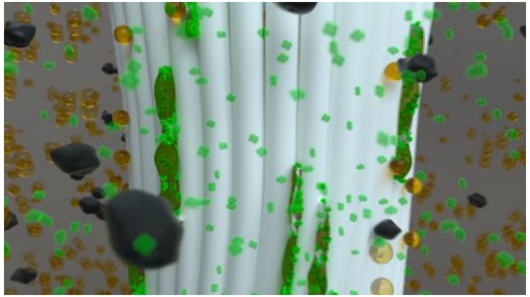


FMBR
35 L

1 m

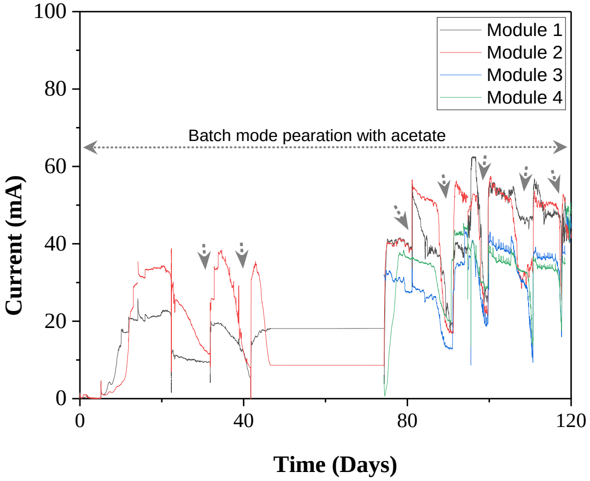
Membrane module (0.1 µm pore size)

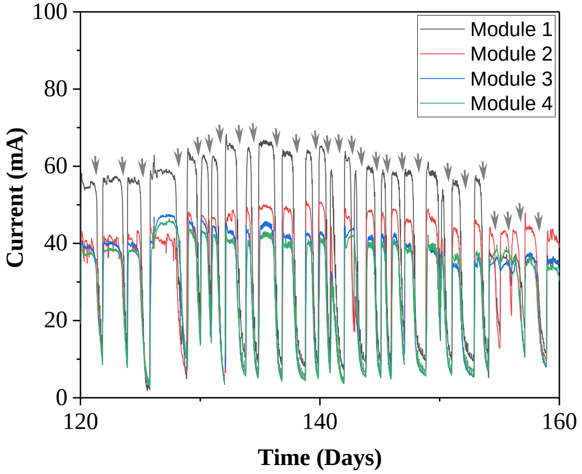
GAC (1mm)

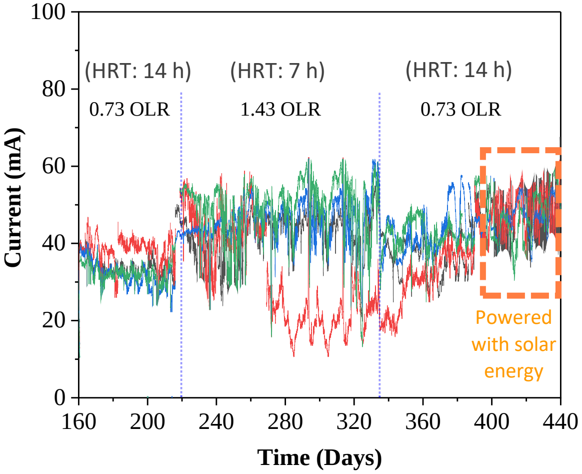


GAC fluidized for 15 min every 2 hours of MBR operation

Performance of pilot-scale AnEFMBR (~450 days of operation)







- Operated with synthetic media (acetate – 10 mM)
- Inoculum: *G. sulfurreducens and D. acetexigens*
- >75% of acetate conversion to electrical current
- 3 moles of H_2 was measured per mole of acetate consumed

- Influent COD: 425 ± 35 mg/L
- Sewage + synthetic media (Starch + Beef extract)
- Fed-batch mode of operation
- CH_4 is present predominantly in biogas
- CH_4 production stabilized at 0.2 L CH_4/g COD removed

- Influent COD: 425 ± 35 mg/L
- Sewage + synthetic media (Starch + Beef extract)
- Continuous mode of operation
- High purity CH_4 produced:
  - 0.73 OLR → 0.21 L CH_4/g COD removed
    -CO_2 concentration below detection limit
  - 1.43 OLR → 0.3 L CH_4/g COD removed
    -biogas consists∼ 10% CO_2

Manuscript in preparation

Energy recovery from pilot-scale AnEFMBR operated with solar energy

The energy for MEC operation is considered zero because this energy was provided by the solar panel

Sewage + synthetic WW

OLR: 0.73 Kg COD/m3/day
Influent COD: 425 ± 35 mg/L

Applied voltage	1 V
CH_4 to electricity	0.34 ± 0.05 kWh/m^3
GAC recirculation in GDM	0.16 kWh/m^3
Feed pump	0.00014 kWh/m^3
Net energy gain	**0.18 ± 0.05 kWh/m^3**

Sewage only

OLR: 0.38 COD/m3/day
Influent COD: 185 ± 30 mg/L

Applied voltage	1 V
CH_4 to electricity	0.14 ± 0.01 kWh/m^3
GAC recirculation in GDM	0.14 kWh/m^3
Feed pump	0.00014 kWh/m^3
Net energy gain	**0.005 ± 0.01 kWh/m^3**

Assuming 33% conversion efficiency of CH_4 to electricity by combustion

Manuscript in preparation

Permeate quality of pilot-scale AnEFMBR at different organic loading rates

Feed	OLR	Influent COD (mg/L)	COD removal (%)	NH_4^+ - N (mg/L)	PO_4^{3-} (mg/L)	Turbidity (NTU)
Sewage + Synthetic WW	1.47	425 ± 35	89 ± 2	28 ± 5	3.2 ± 3	0
Sewage + Synthetic WW	0.73	425 ± 35	92 ± 3	24 ± 3	2.8 ± 2	0
Sewage	0.38	180 ± 30	79 ± 5	23 ± 4	2.4 ± 3	0

Sewage

TSE

Treated sewage effluent (TSE)

Manuscript in preparation

Permeate quality of pilot-scale AnEFMBR at different organic loading rates

Feed	OLR	Influent COD (mg/L)	COD removal (%)	NH_4^+ - N (mg/L)	PO_4^{3-} (mg/L)	Turbidity (NTU)
Sewage + Synthetic WW	1.47	425 ± 35	89 ± 2	28 ± 5	3.2 ± 3	0
Sewage + Synthetic WW	0.73	425 ± 35	92 ± 3	24 ± 3	2.8 ± 2	0
Sewage	0.38	180 ± 30	79 ± 5	23 ± 4	2.4 ± 3	0

Agriculture reuse

Sewage

TSE

Treated sewage effluent (TSE)

Manuscript in preparation

Permeate quality of pilot-scale AnEFMBR at different organic loading rates

Feed	OLR	Influent COD (mg/L)	COD removal (%)	NH_4^+ - N (mg/L)	PO_4^{3-} (mg/L)	Turbidity (NTU)
Sewage + Synthetic WW	1.47	425 ± 35	89 ± 2	28 ± 5	3.2 ± 3	0
Sewage + Synthetic WW	0.73	425 ± 35	92 ± 3	24 ± 3	2.8 ± 2	0
Sewage	0.38	180 ± 30	79 ± 5	23 ± 4	2.4 ± 3	0

Agriculture reuse

Sewage

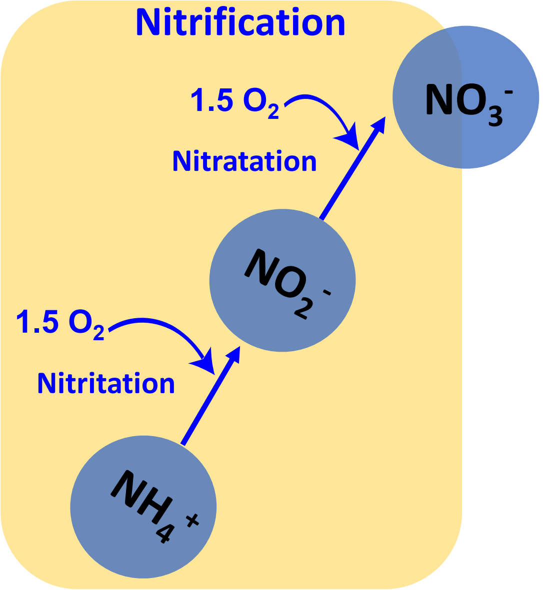
TSE

Treated sewage effluent (TSE)

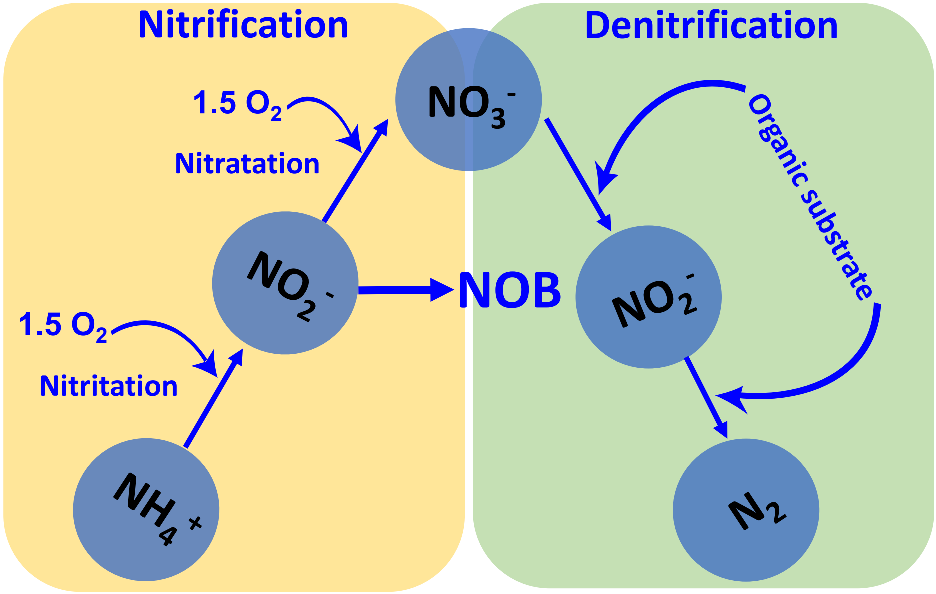
What about other non-potable reuse applications that require removal of ammonium?

Manuscript in preparation

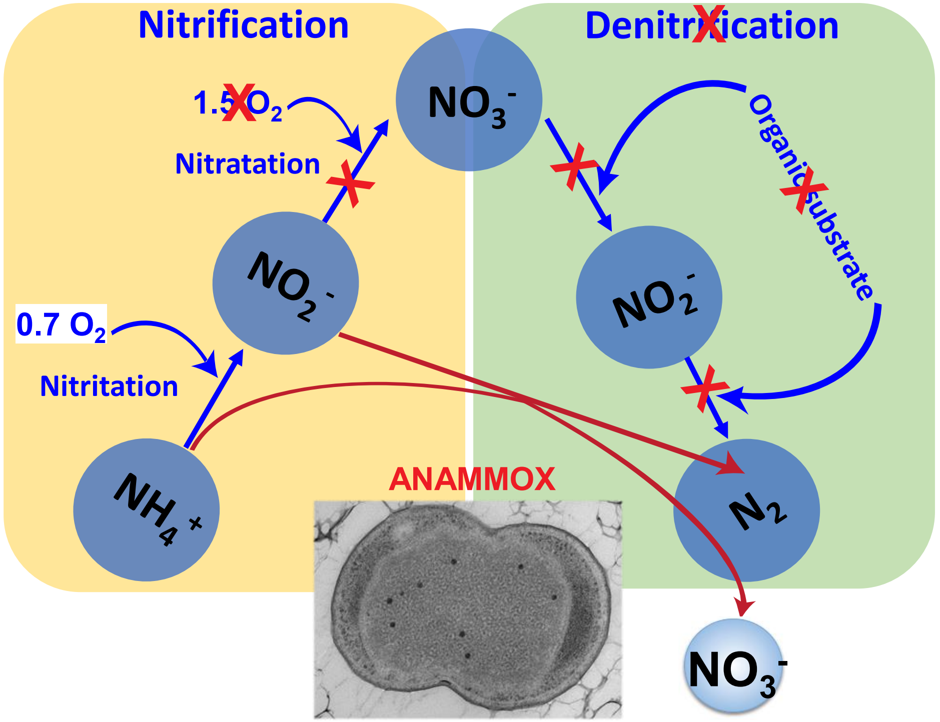
What is the most energy-efficient and sustainable bioprocess for nitrogen removal?



What is the most energy-efficient and sustainable bioprocess for nitrogen removal?

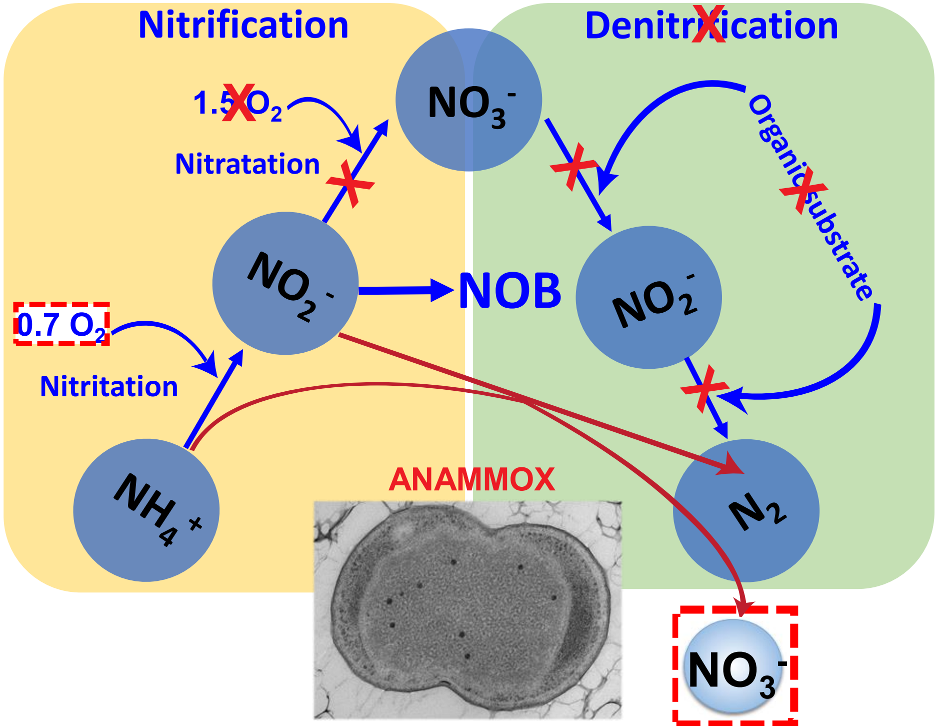


What is the most energy-efficient and sustainable bioprocess for nitrogen removal?



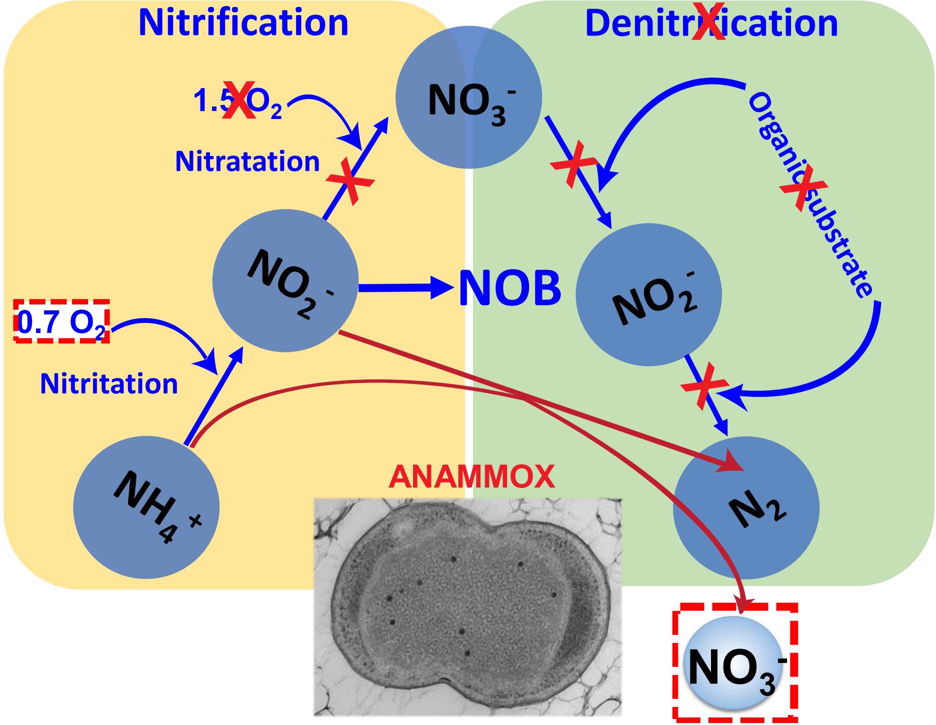
- **60% reduction in energy**
- **100% reduction in carbon demand**
- **75% reduction in sludge production**
- **Less/no N_2O (GHG) emission**

What is the most energy-efficient and sustainable bioprocess for nitrogen removal?



- 60% reduction in energy
- 100% reduction in carbon demand
- 75% reduction in sludge production
- Less/no N_2O (GHG) emission

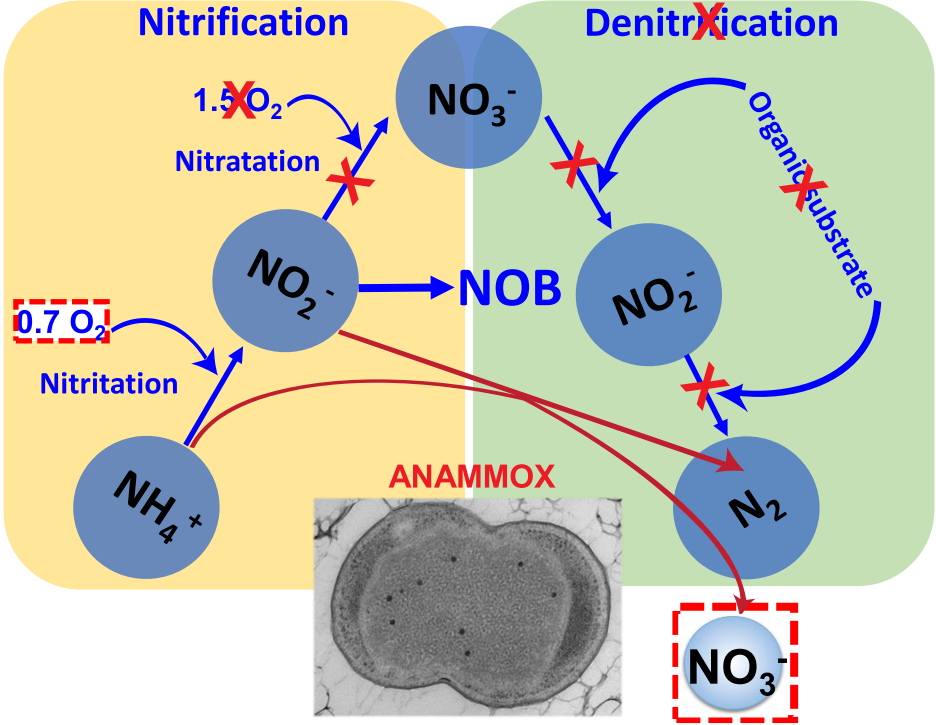
What is the most energy-efficient and sustainable bioprocess for nitrogen removal?



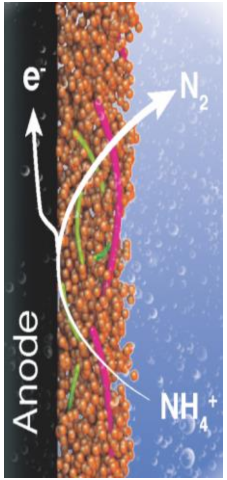
- 60% reduction in energy
- 100% reduction in carbon demand
- 75% reduction in sludge production
- Less/no N_2O (GHG) emission

- Genome encodes for 60 *c*-type cytochromes
- 10^7 heme-bound iron atoms (red color)
- Have homologs of *Geobacter* and *Shewanella* multi-heme *c*-type cytochromes that are responsible for EET

What is the most energy-efficient and sustainable bioprocess for nitrogen removal?



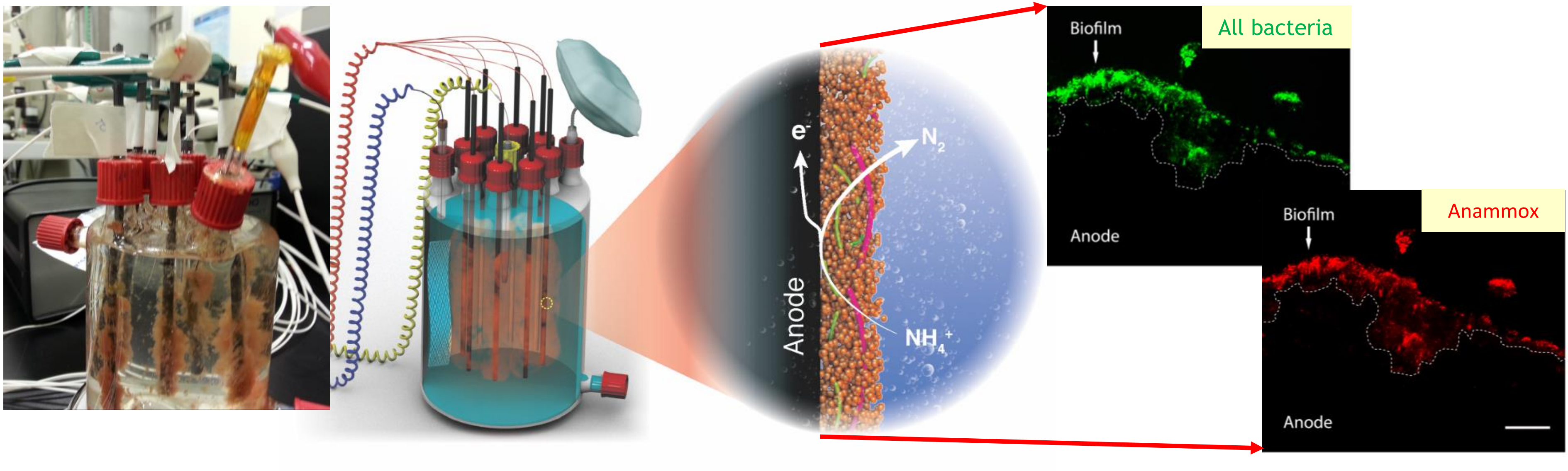
- 60% reduction in energy
- 100% reduction in carbon demand
- 75% reduction in sludge production
- Less/no N_2O (GHG) emission



- **Genome encodes for 60 *c*-type cytochromes**
- **10^7 heme-bound iron atoms (red color)**
- **Have homologs of *Geobacter* and *Shewanella* multi-heme *c*-type cytochromes that are responsible for EET**

Electro-anammox: a novel anaerobic bioprocess for nitrogen removal

Dario Rangel Shaw

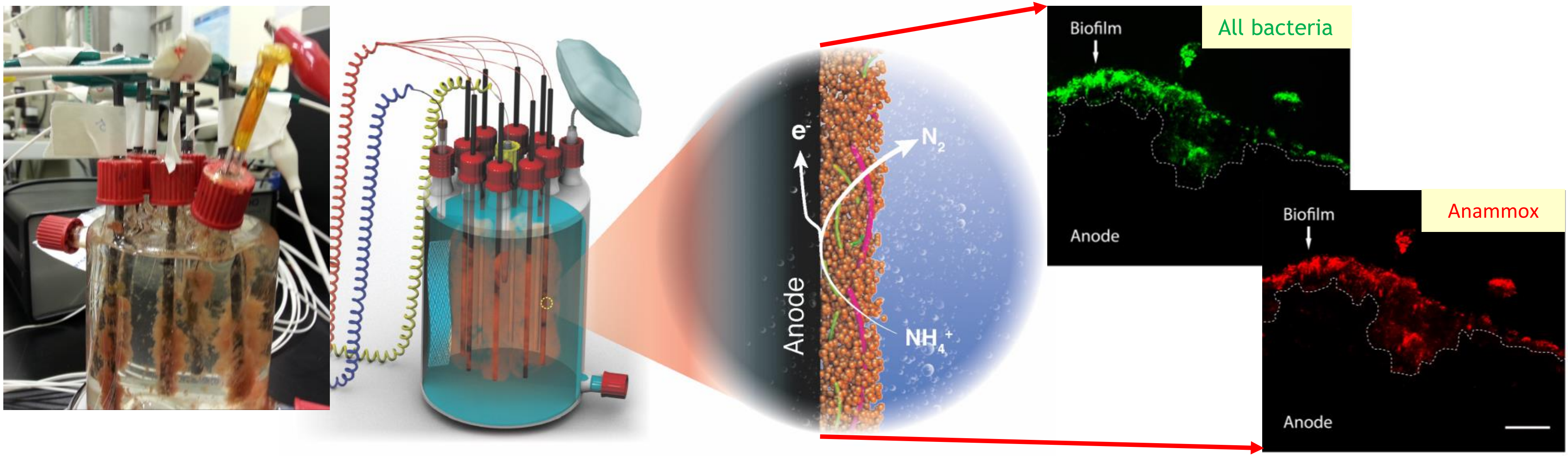


Conventional anammox: $NH_4^+ + NO_2^- \rightarrow N_2 + NO_3^-$

Nature Communications, 2020, 11:2058; **2020 Best Discovery Award from the International Society for Microbial Electrochemistry and Technology (ISMET)**

Electro-anammox: a novel anaerobic bioprocess for nitrogen removal

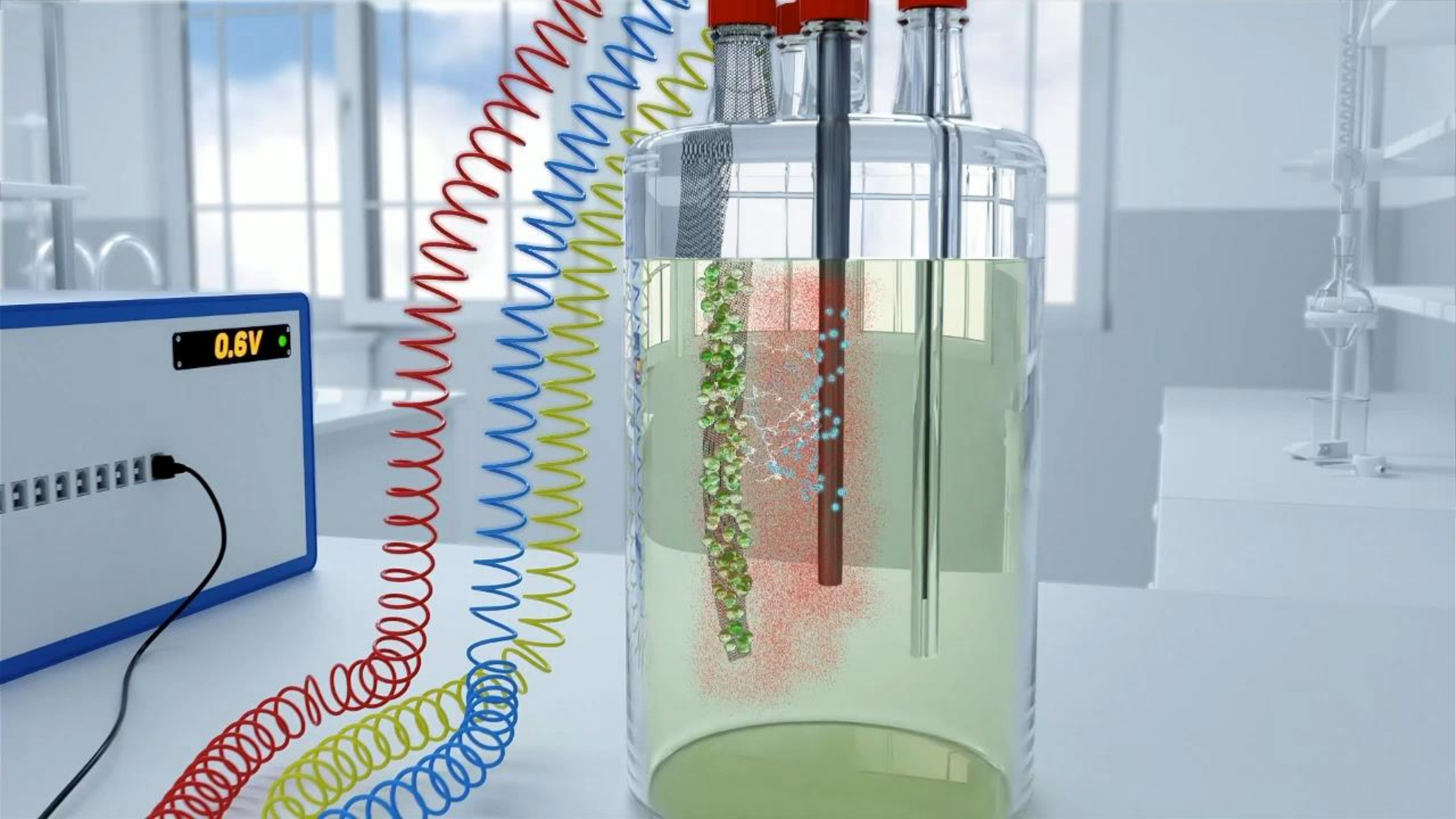
Dario Rangel Shaw



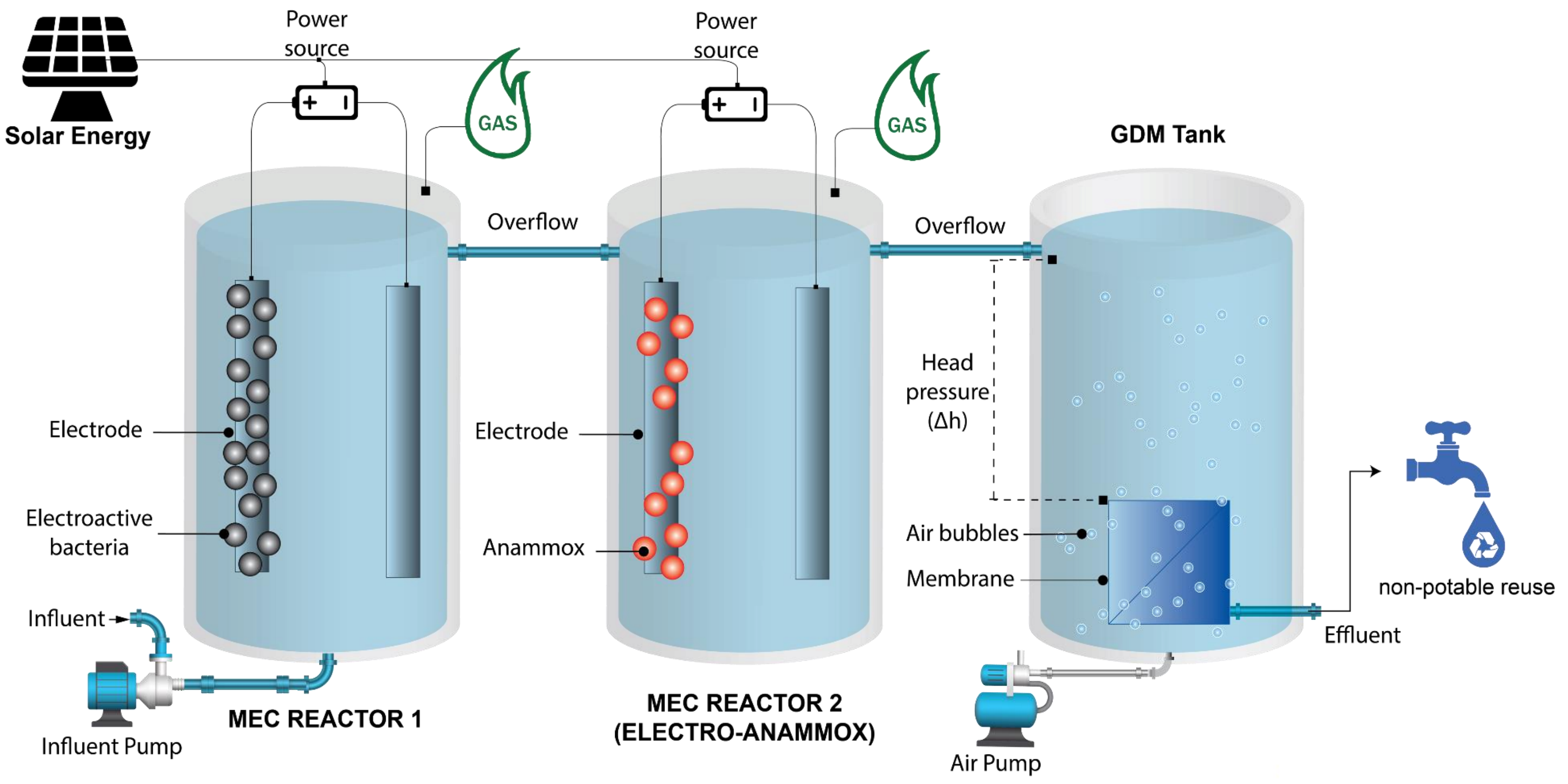
Electro-anammox: $NH_4^+ + \cancel{NO_2^-} \rightarrow N_2 + \cancel{NO_3^-}$

- **Complete nitrogen removal with no need for aeration**
- **No NO_3^- as byproduct; no further polishing of effluent is required**
- **Possibility of carbon- and energy-neutral oxidation of ammonium when coupled to renewables**
- **Electric current from ammonium oxidation can be stored as H_2**

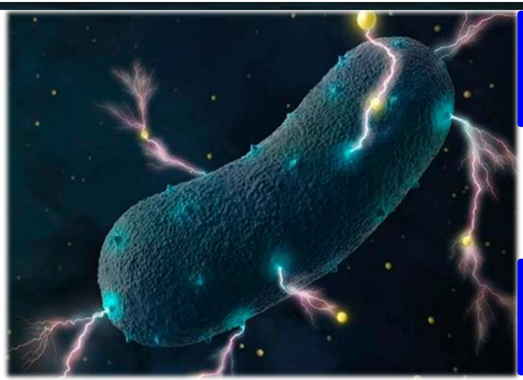
Nature Communications, 2020, 11:2058; **2020 Best Discovery Award from the International Society for Microbial Electrochemistry and Technology (ISMET)**


0.6V

What's next? Integrating AnEFMBR with electro-anammox for energy-neutral WWT for non-potable reuse

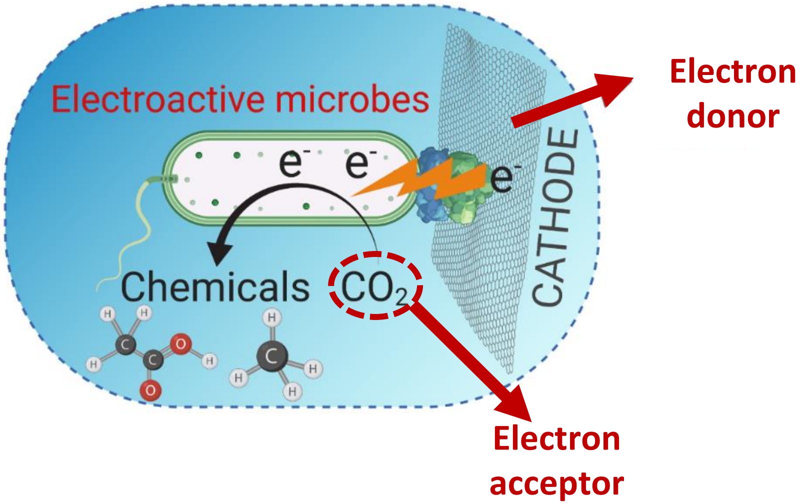


1. Microbial electrochemical systems

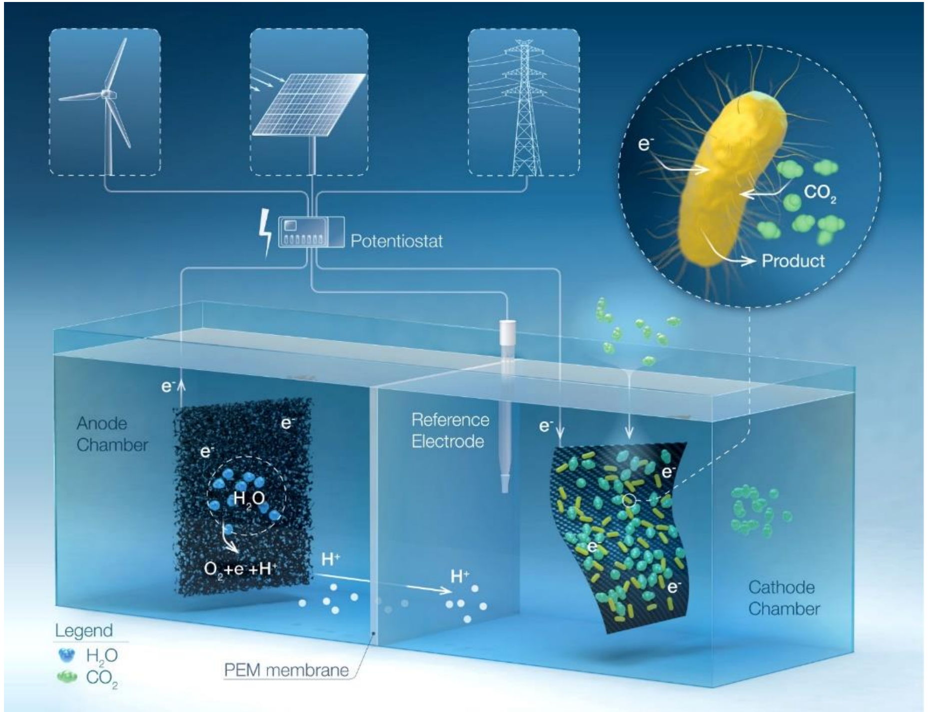


Theme 1: Microbial electrolysis cell for achieving energy-neutral domestic wastewater treatment and reuse

Theme 2: Microbial electrosynthesis for converting CO_2 to chemicals and fuels



Theme 2: Microbial electrosynthesis for converting CO_2 to chemicals

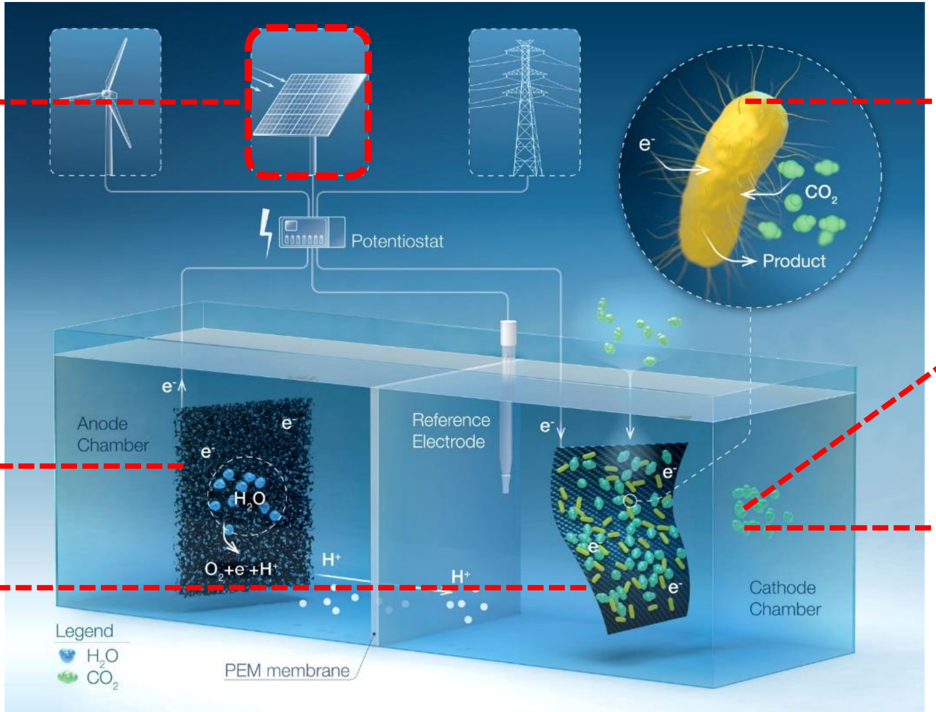


ACS Sustainable Chemistry and Engineering, 2023, 11, 1100-1109; ***Chemical Engineering Journal,*** 2022, 450, 138230; ***Advanced Functional Materials***, 2021, 31, 2010916; ***Bioresource Technology***, 2021, 319, 124177; ***Scientific Reports***, 2021, 10:19824; ***Science of the Total Environment***, 2020, 142668; ***Applied Energy***, 2020, 278, 115684; ***Green Chemistry***, 2020, 22, 5610–5618; ***Bioresource Technology***, 2020, 302, 122863; ***Frontiers in Microbiology***, 2019, 10:2563; ***Microbiology Resource Announcements***, 2019, 8(45), e01138-19; ***Frontiers in Microbiology***, 2019, 10:1747; ***Chemistry of Materials***, 2019, 31, 3686-3693 ; ***Advanced Functional Materials***, 2018, 28, 1804860**;** ***Journal of Materials Chemistry A***, 2018, 6, 17201-17211; ***Advanced Materials***, 2018, 30, 1707072; **Patents: WO 2020/031090 A1, WO 2019/197992 A1, US 2018/0346935 A1**

Theme 2: Microbial electrosynthesis for converting CO_2 to chemicals

Can we use MES as a platform for solar-to-chemical conversion?

Can we reduce the amount of catalyst required to drive electrocatalysis?



What is the effect of inoculum source on enriching for specific CO_2 reducing microbes?

Can we reduce CO_2 mass transfer limitation?

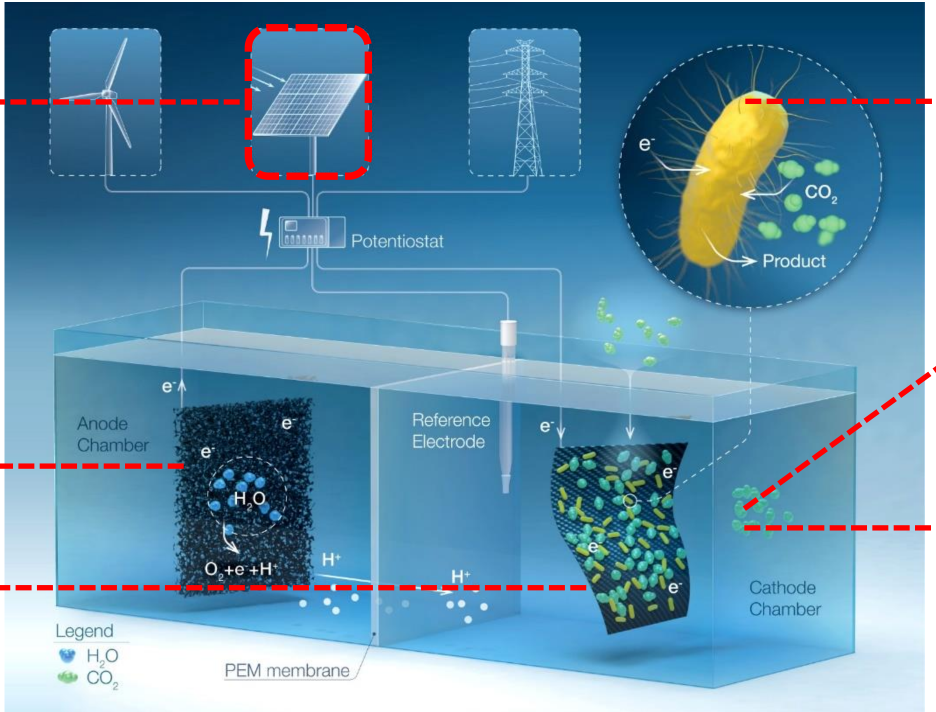
What is the effect of CO_2 concentration and flow rate on stability?

ACS Sustainable Chemistry and Engineering, 2023, 11, 1100-1109; *Chemical Engineering Journal,* 2022, 450, 138230; *Advanced Functional Materials*, 2021, 31, 2010916; *Bioresource Technology*, 2021, 319, 124177; *Scientific Reports*, 2021, 10:19824; *Science of the Total Environment*, 2020, 142668; *Applied Energy*, 2020, 278, 115684; *Green Chemistry*, 2020, 22, 5610–5618; *Bioresource Technology*, 2020, 302, 122863; *Frontiers in Microbiology*, 2019, 10:2563; *Microbiology Resource Announcements*, 2019, 8(45), e01138-19; *Frontiers in Microbiology*, 2019, 10:1747; *Chemistry of Materials*, 2019, 31, 3686-3693 ; *Advanced Functional Materials*, 2018, 28, 1804860; *Journal of Materials Chemistry A*, 2018, 6, 17201-17211; *Advanced Materials*, 2018, 30, 1707072; **Patents: WO 2020/031090 A1, WO 2019/197992 A1, US 2018/0346935 A1**

Theme 2: Microbial electrosynthesis for converting CO_2 to chemicals

Can we use MES as a platform for solar-to-chemical conversion?

What is the effect of inoculum source on enriching for specific CO_2 reducing microbes?



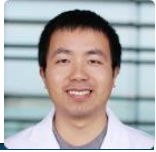
Can we reduce CO_2 mass transfer limitation?

Can we reduce the amount of catalyst required to drive electrocatalysis?

What is the effect of CO_2 concentration and flow rate on stability?

ACS Sustainable Chemistry and Engineering, 2023, 11, 1100-1109; ***Chemical Engineering Journal,*** 2022, 450, 138230; ***Advanced Functional Materials***, 2021, 31, 2010916; ***Bioresource Technology***, 2021, 319, 124177; ***Scientific Reports***, 2021, 10:19824; ***Science of the Total Environment***, 2020, 142668; ***Applied Energy***, 2020, 278, 115684; ***Green Chemistry***, 2020, 22, 5610–5618; ***Bioresource Technology***, 2020, 302, 122863; ***Frontiers in Microbiology***, 2019, 10:2563; ***Microbiology Resource Announcements***, 2019, 8(45), e01138-19; ***Frontiers in Microbiology***, 2019, 10:1747; ***Chemistry of Materials***, 2019, 31, 3686-3693 ; ***Advanced Functional Materials***, 2018, 28, 1804860**;** ***Journal of Materials Chemistry A***, 2018, 6, 17201-17211; ***Advanced Materials***, 2018, 30, 1707072; **Patents: WO 2020/031090 A1, WO 2019/197992 A1, US 2018/0346935 A1**

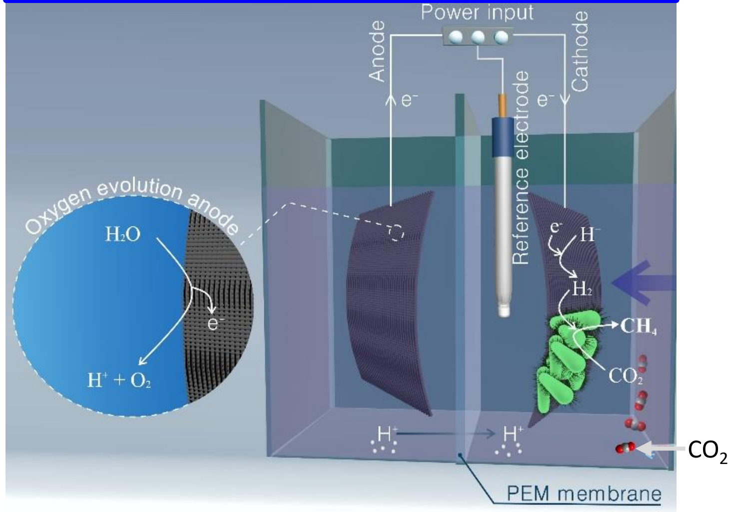
Improved microbial electrosynthesis of CH_4 from CO_2 using dual function cathode



Manal Al Gahtani

Bin Bian

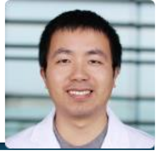
Flat cathode with CO_2-gas bubbling



Advanced Functional Materials, 2018, 28, 1804860

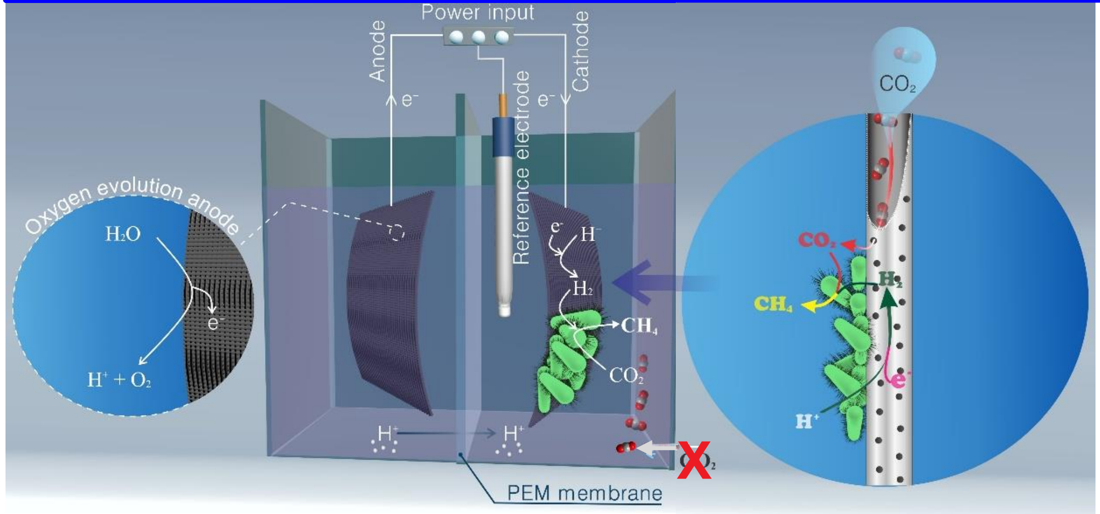
Improved microbial electrosynthesis of CH_4 from CO_2 using dual function cathode

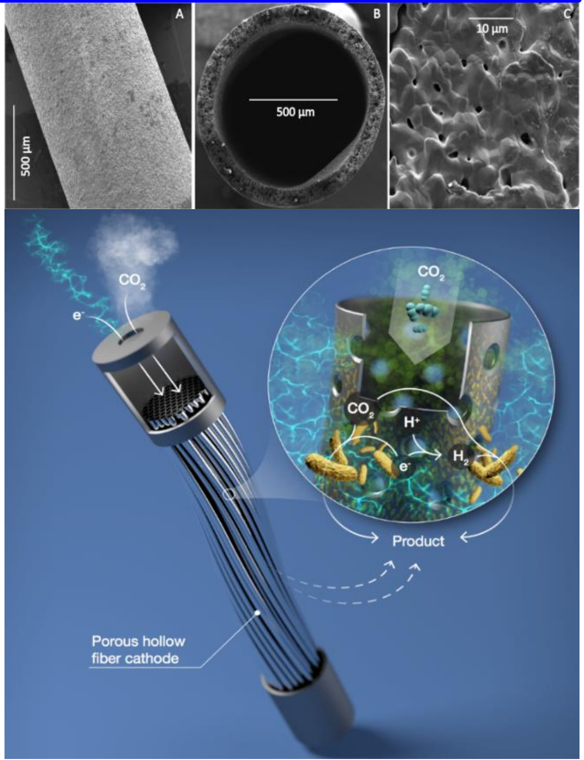
Manal Al Gahtani



Bin Bian

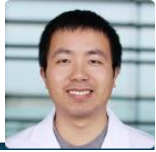
Flat cathode with CO_2-gas bubbling	Dual function nickel-based electrocatalytic HFM





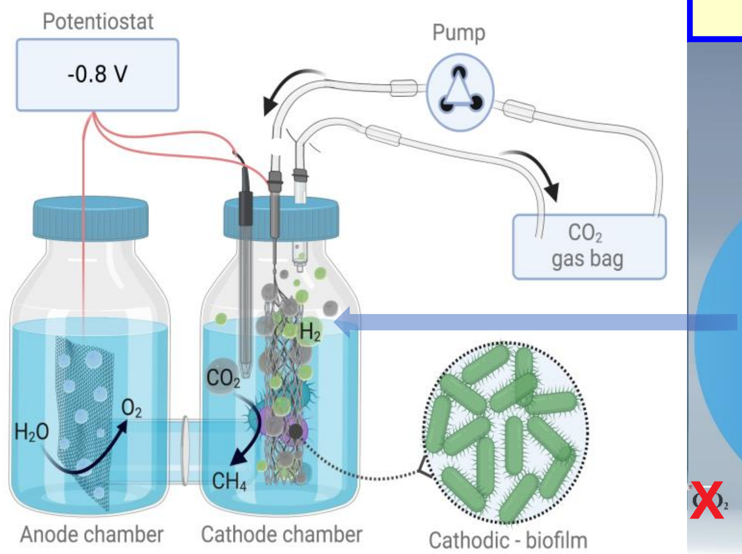
Advanced Functional Materials, 2018, 28, 1804860

Improved microbial electrosynthesis of CH_4 from CO_2 using dual function cathode

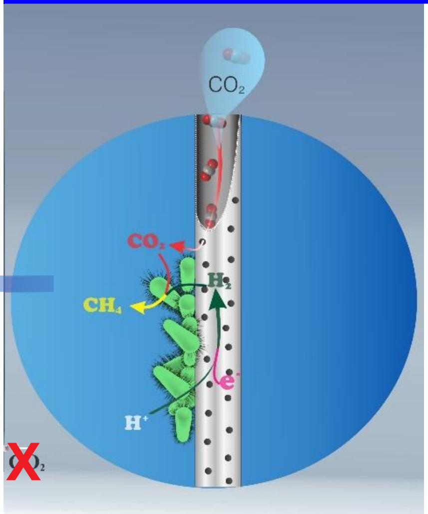


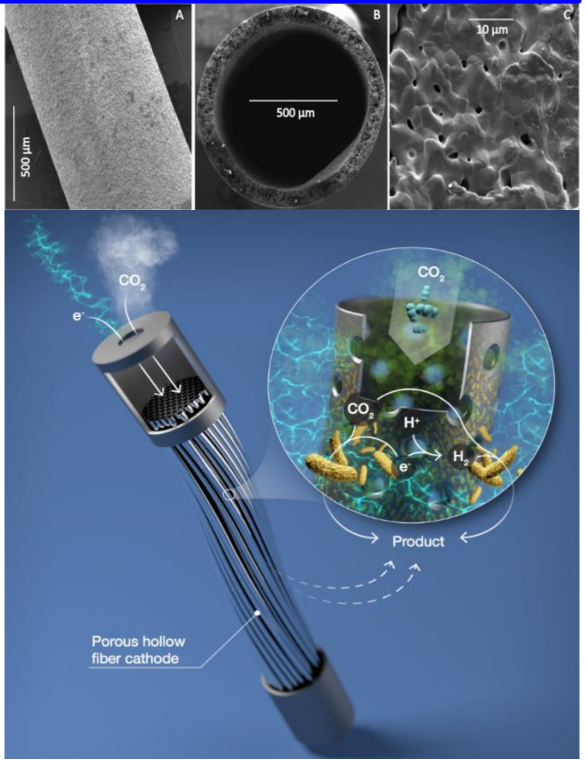
Manal Al Gahtani

Bin Bian



Dual function nickel-based electrocatalytic HFM



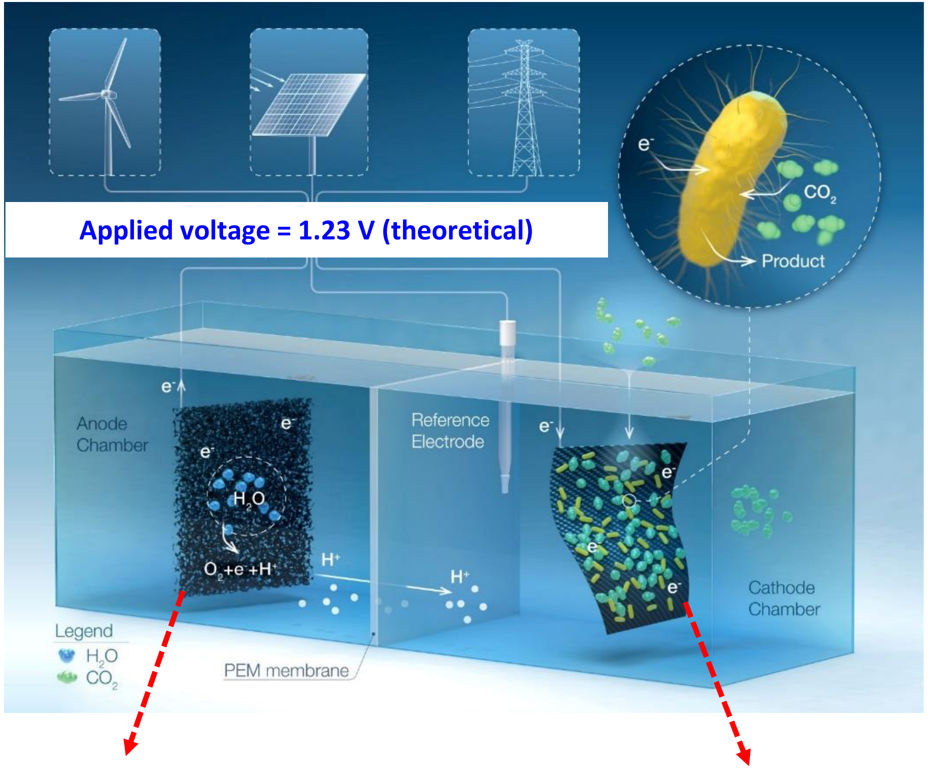


Conversion of CO_2 to CH_4 with high Faradaic efficiency (> 80%) compared to 3% through gas-bubbling in electrolyte

$$CO_2 + 8e^- + 8H^+ \rightarrow CH_4 + 2H_2O$$

Advanced Functional Materials, 2018, 28, 1804860

High energy input (applied voltage) and expensive catalysts are required to overcome the anodic and cathodic overpotentials



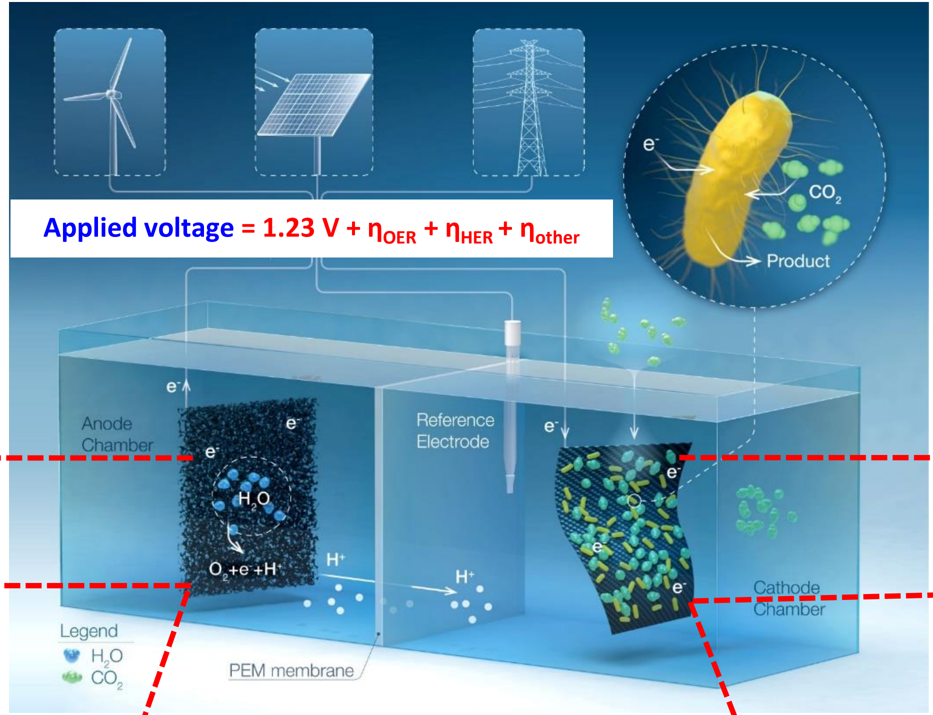
Oxygen evolution reaction (OER):

$2H_2O \rightarrow O_2 + 4H^+ + 4e^-$ E°= 1.23V vs. RHE

Hydrogen evolution reaction (HER):

$2H^+ + 2e^- \rightarrow H_2$ E°= 0.00 V vs. RHE

High energy input (applied voltage) and expensive catalysts are required to overcome the anodic and cathodic overpotentials



Ir- and Ru-based

Pt-based

Kinetic overpotential (η_{OER}) for OER

Kinetic overpotential (η_{HER}) for HER

Oxygen evolution reaction (OER):

$2H_2O \rightarrow \mathbf{O_2} + 4H^+ + 4e^-$ E°= 1.23V vs. RHE

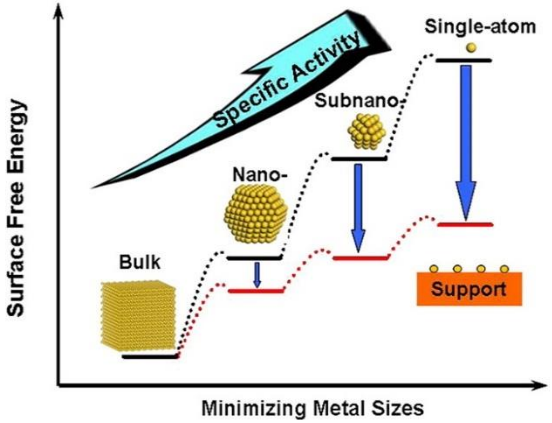
Hydrogen evolution reaction (HER):

$2H^+ + 2e^- \rightarrow \mathbf{H_2}$ E°= 0.00 V vs. RHE

Synthesis of single-atom metal (SA-M) catalysts by *G. sulfurreducens*

Rodrigo Sandoval

Dr. Krishna Katuri

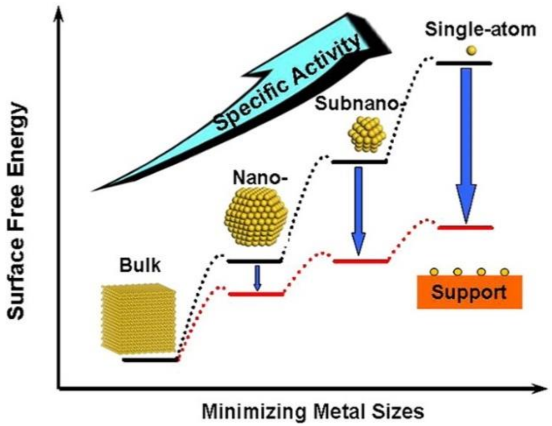


Acc. Chem. Res. 2013, 46, 8, 1740-1748

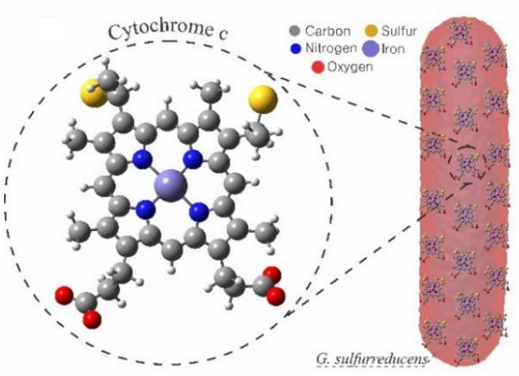
Advantages: maximum atomic utilization, excellent selectivity, and most exposed active sites

Synthesis of single-atom metal (SA-M) catalysts by *G. sulfurreducens*

Rodrigo Sandoval
Dr. Krishna Katuri



Acc. Chem. Res. 2013, 46, 8, 1740-1748

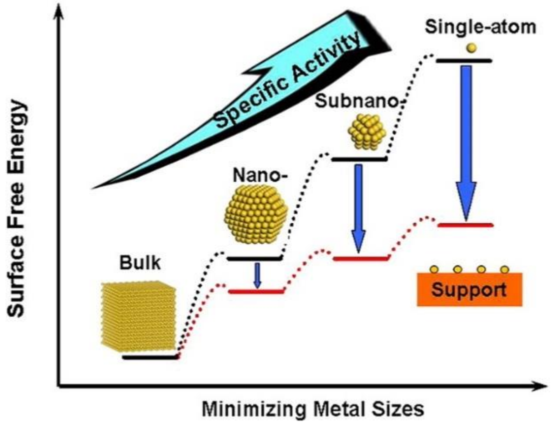


Advantages: maximum atomic utilization, excellent selectivity, and most exposed active sites

Synthesis of single-atom metal (SA-M) catalysts by *G. sulfurreducens*

Rodrigo Sandoval

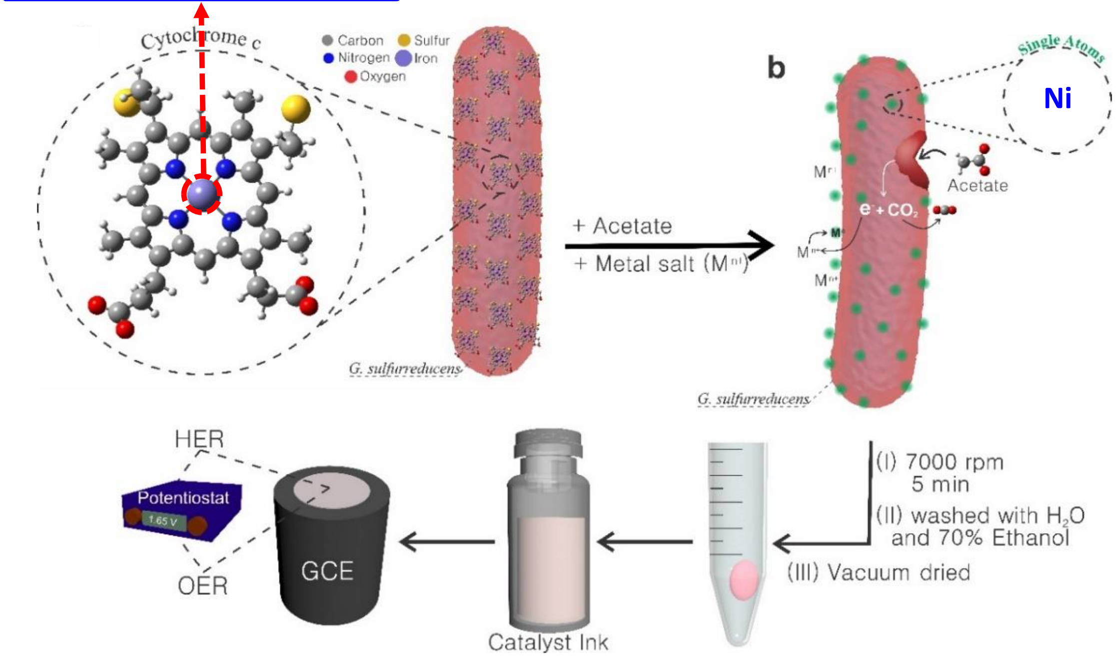
Dr. Krishna Katuri



Acc. Chem. Res. 2013, 46, 8, 1740-1748

Advantages: maximum atomic utilization, excellent selectivity, and most exposed active sites

Reduce extracellular electron acceptors

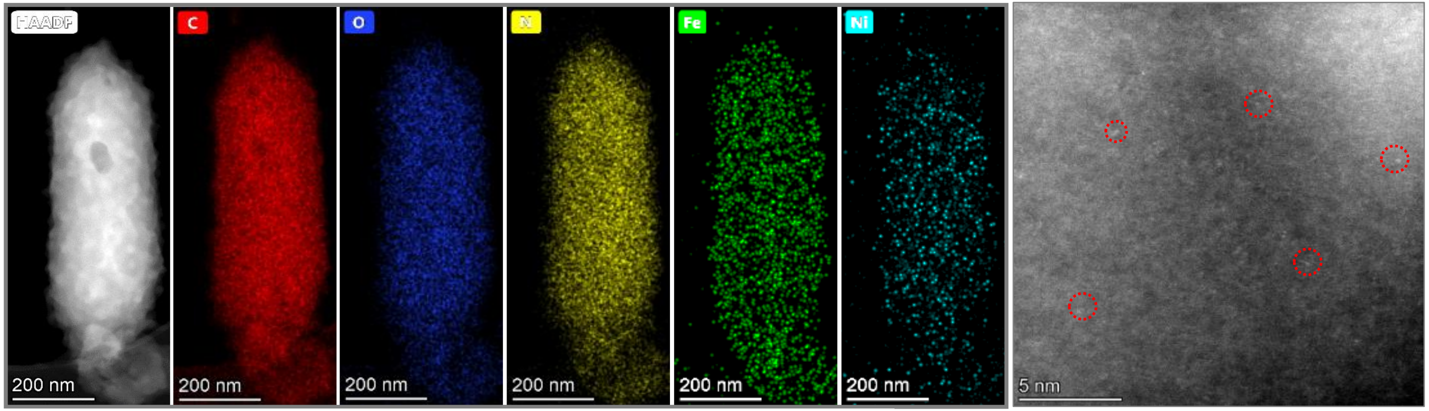


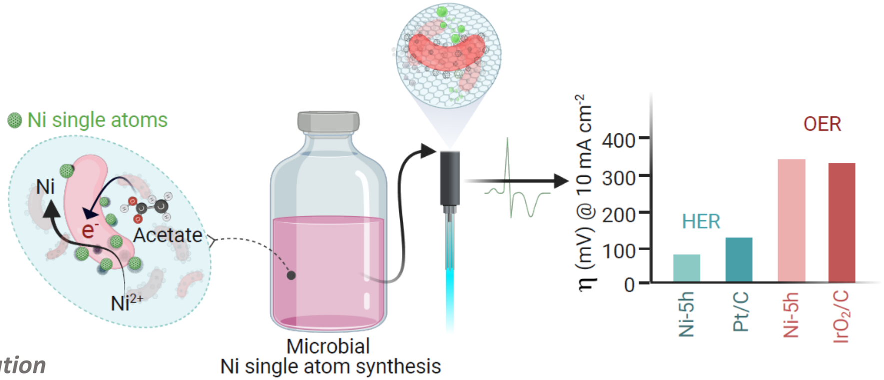
Nickel single atom synthesis on the surface of *G. sulfurreducens* cells

Rodrigo Sandoval

Dr. Krishna Katuri

Energy-dispersive X-ray spectroscopy (EDX) elemental mapping High-angle annular dark-field scanning transmission electron microscopy





- Total overpotential for Ni-SA was 410 mv compared to 440 mv (Pt/C and IrO_2)
- 7 times lower mass loading (0.0015 mg Ni cm^{-2}) than Pt (0.01 mg Pt cm^{-2}) or IrO_2 (0.01 mg IrO_2 cm^{-2})

Manuscript in preparation

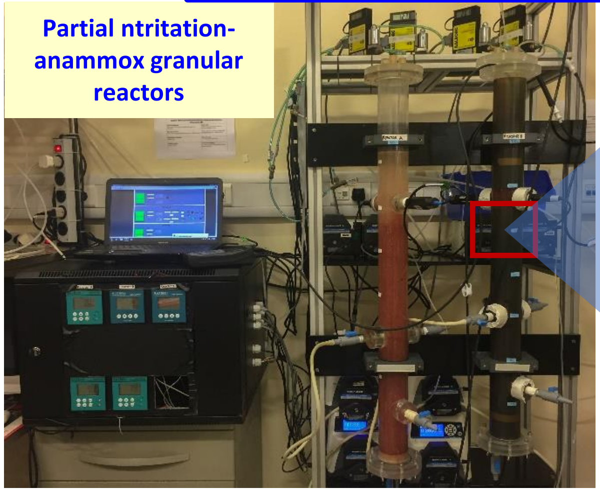
Dr. Dario Rangel Shaw

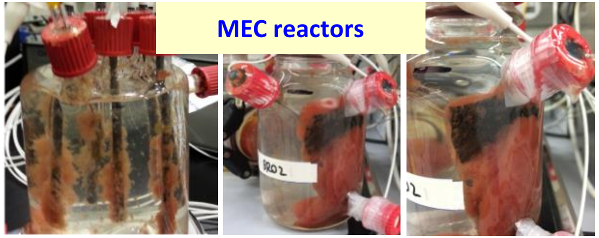
2. Anaerobic ammonium oxidation (anammox)

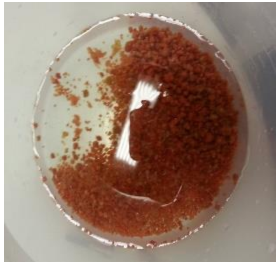
Julian Gonzalez

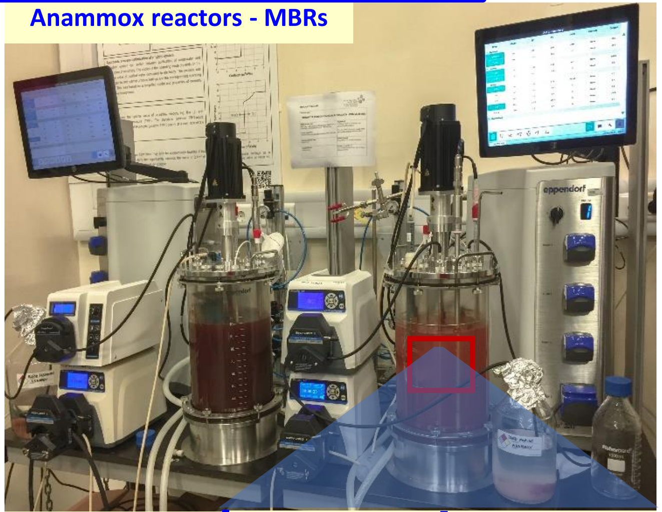
Theme 1: Integrating granular anammox process for mainstream WWT to achieve energy neutral treatment

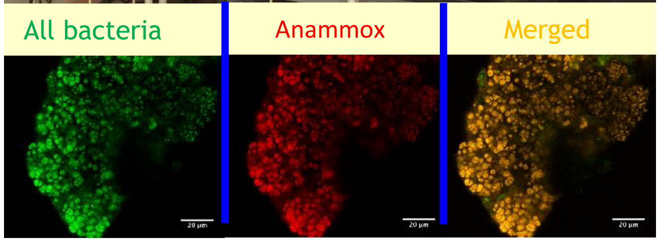
Theme 2: Partial nitritation/marine anammox process for saline WWT







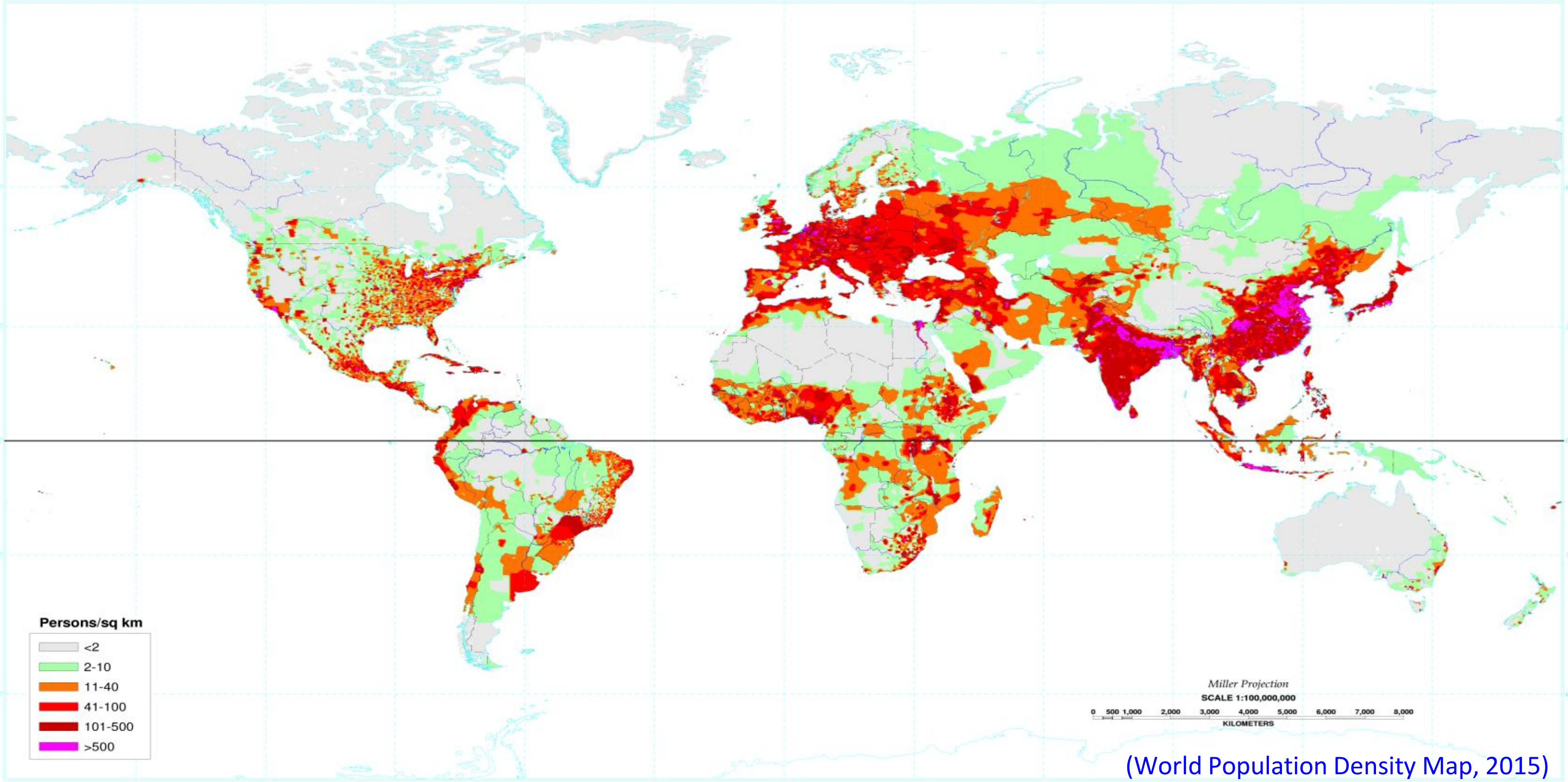




Scientific Reports, 2015; 5:14316; *Scientific Reports*, 2016, 6:28327; *Water Research*, 2018, 143, 10-18

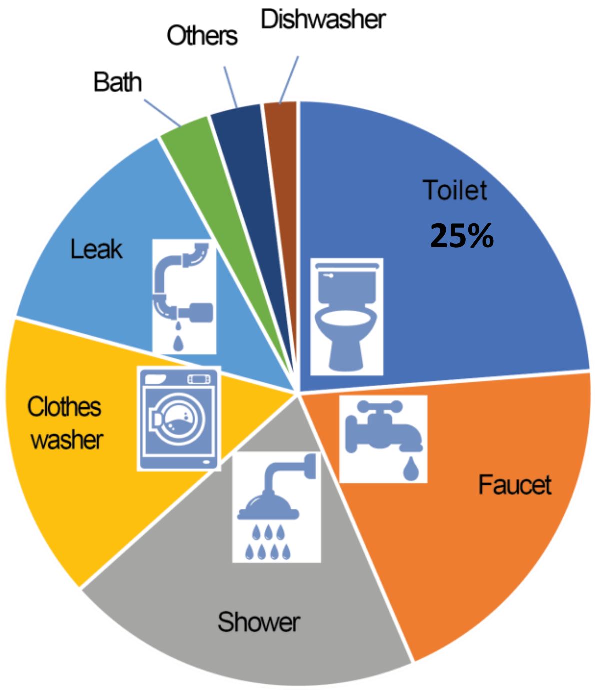
Over 50% of the world's population resides within 60 km of the coast

Demand on freshwater resources for potable and non-potable uses will continue increasing due to the rapidly growing human population



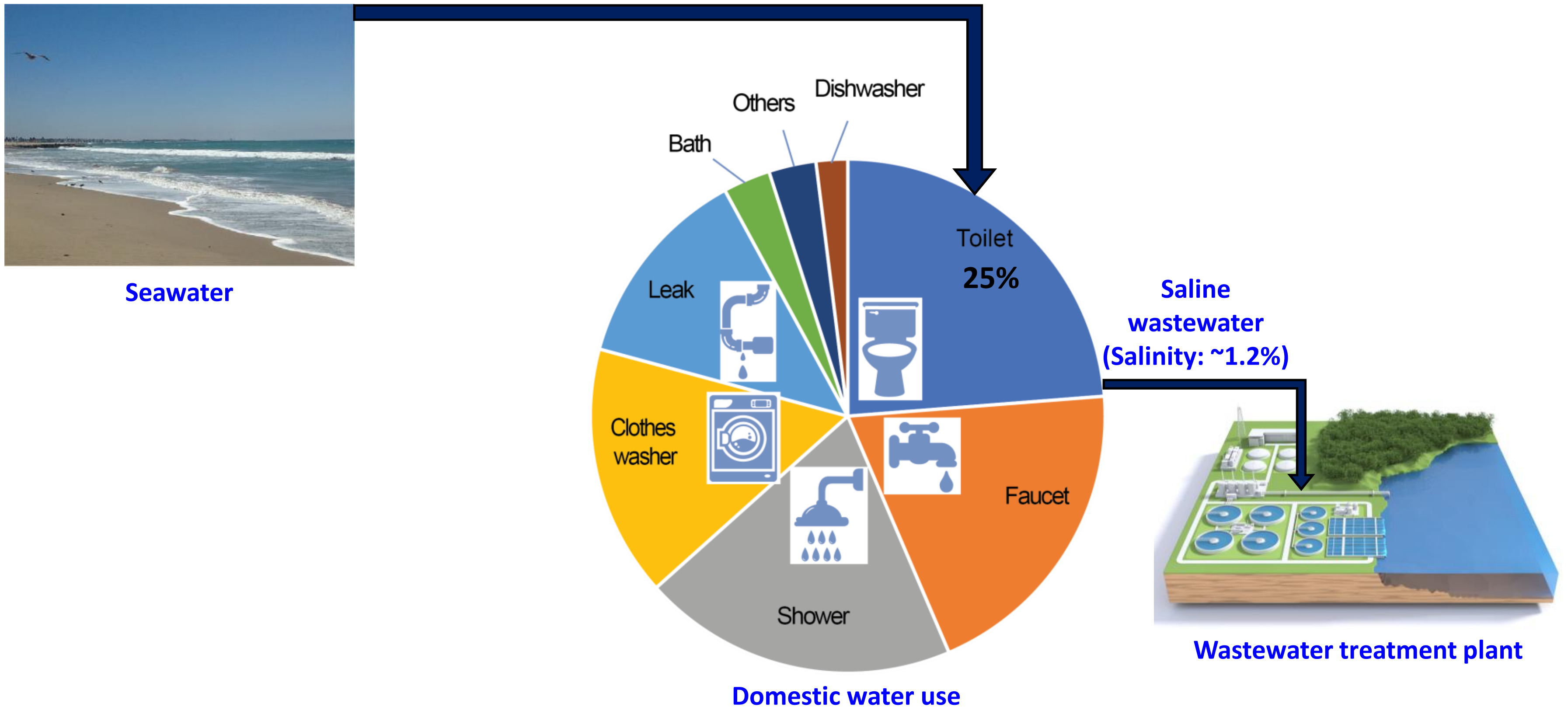
(World Population Density Map, 2015)

Seawater for toilet flushing

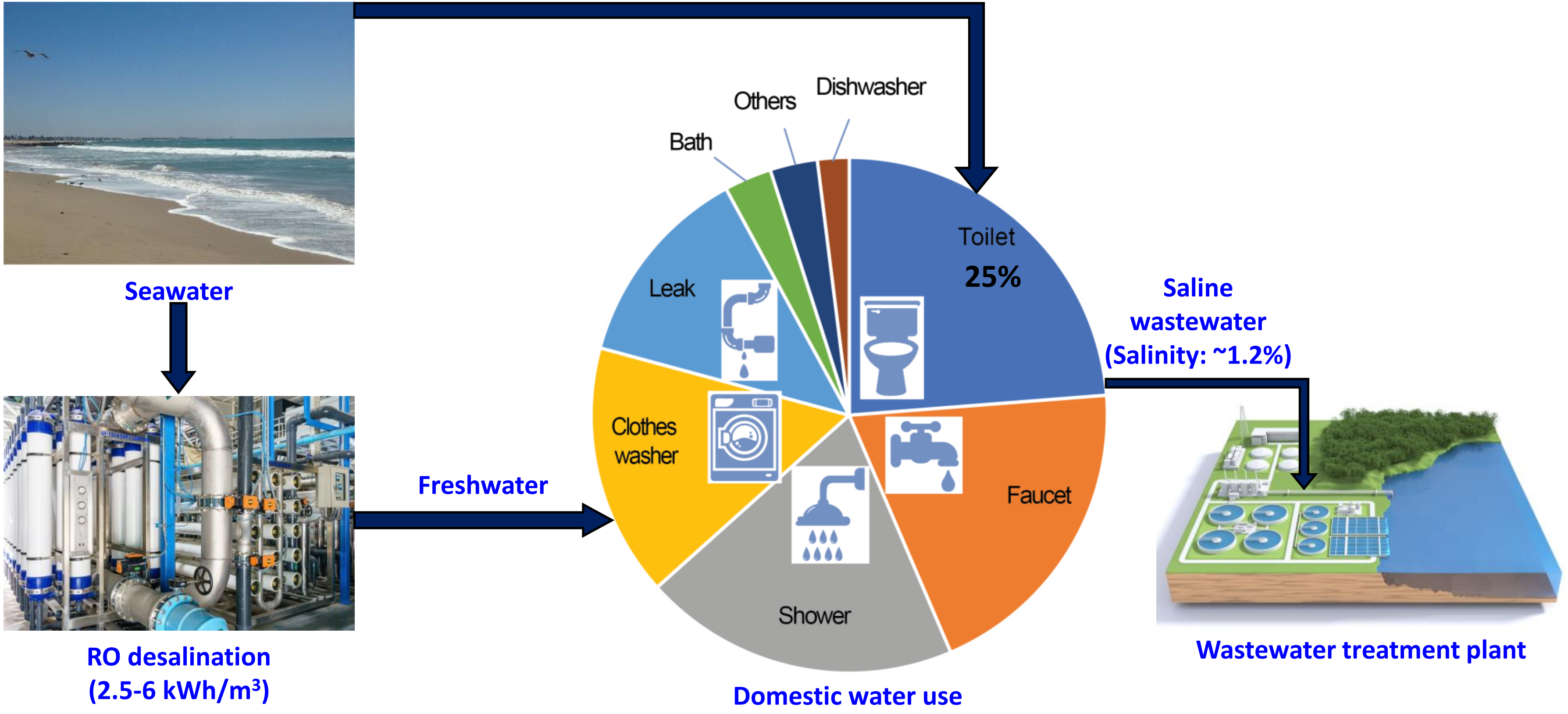


Domestic water use

Seawater for toilet flushing



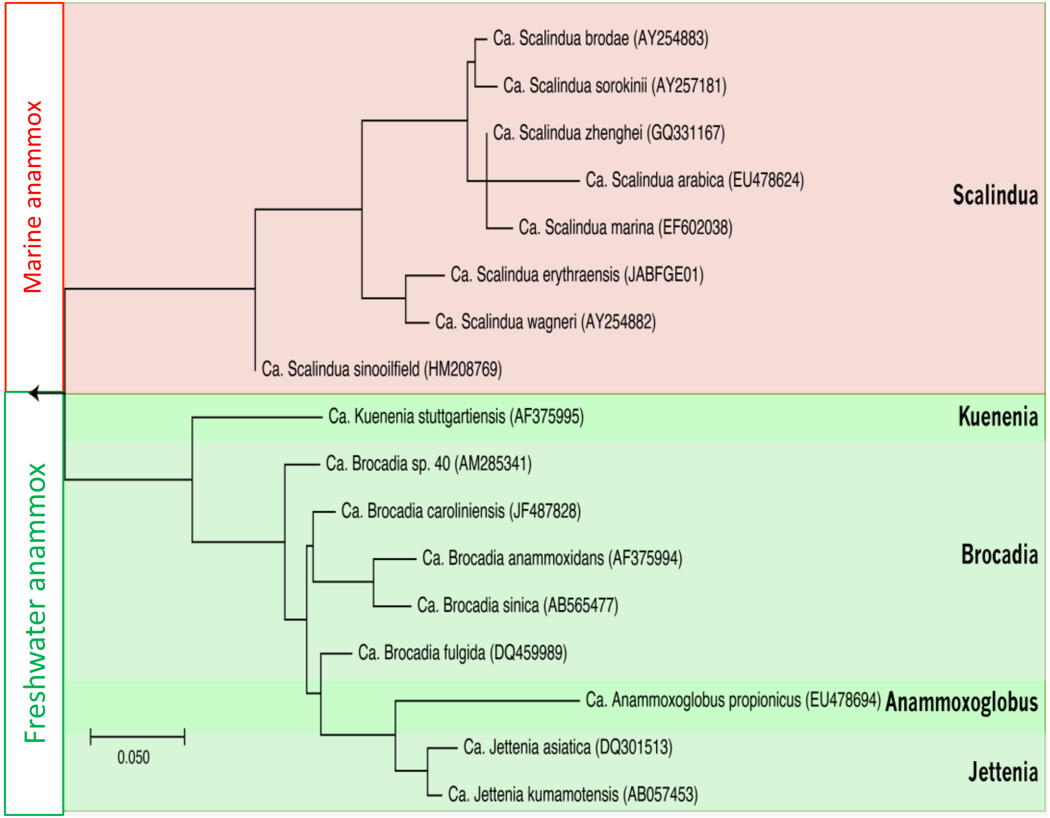
Seawater for toilet flushing



Seawater treatment facility in Hong Kong: supply seawater for toilet flushing

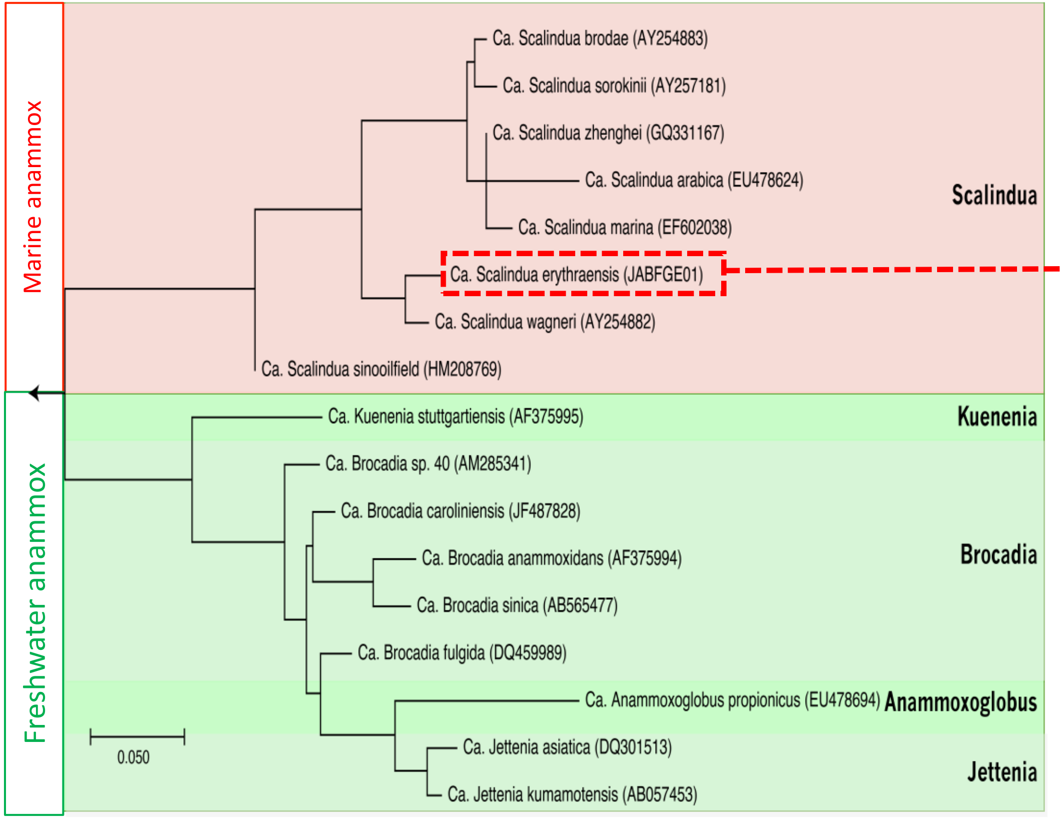
Pumps at Hong Kong's Wan Chai Seawater Treatment Facility: supply toilets with seawater that is used only for flushing. Image: Alok Gupta via Citiscope

Ca. Scalindua erythraensis: a novel marine anammox bacterium enriched from the Red Sea

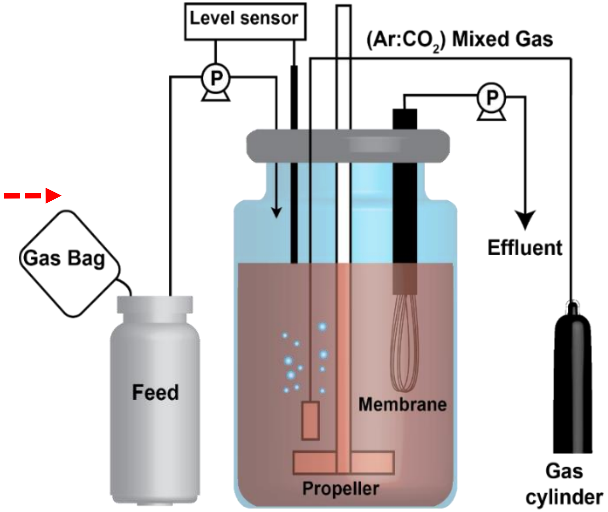


Microbiology Resource Announcements, 2019, 8 (999), e00297-19; ***Frontiers in Microbiology***, 2020, 11:1637; ***Water Research***, 2020, 170, 115345

Ca. Scalindua erythraensis: a novel marine anammox bacterium enriched from the Red Sea



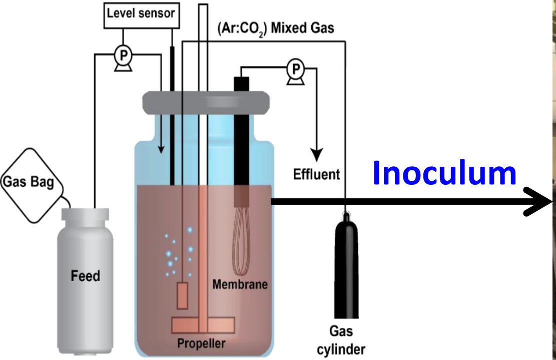
- **Intrinsic tolerance to salinity**

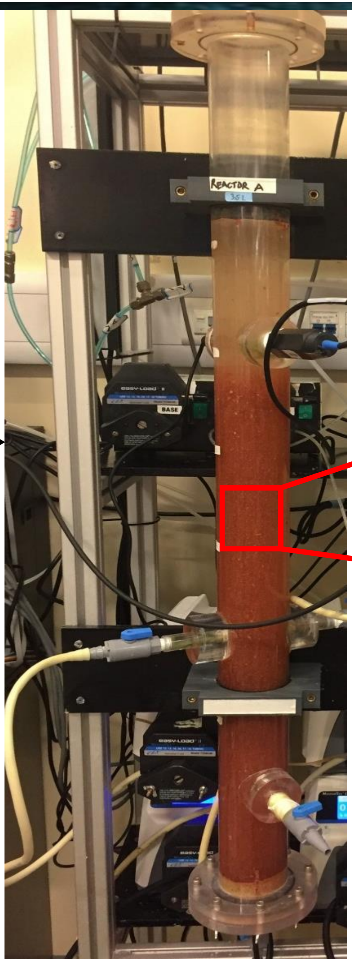


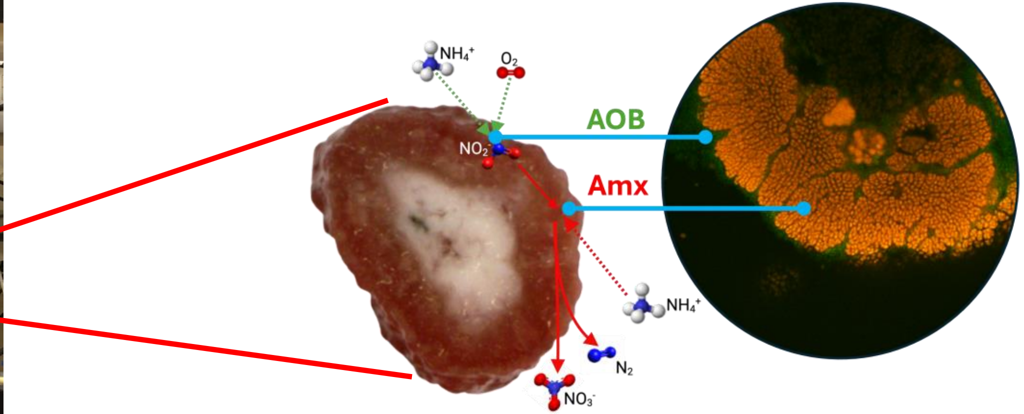
- **Stable reactor performance with NRR of 0.27±0.01 kg–N m^{-3} d^{-1} and ~92% N-removal efficiency**

Microbiology Resource Announcements, 2019, 8 (999), e00297-19; *Frontiers in Microbiology*, 2020, 11:1637; *Water Research,* 2020, 170, 115345

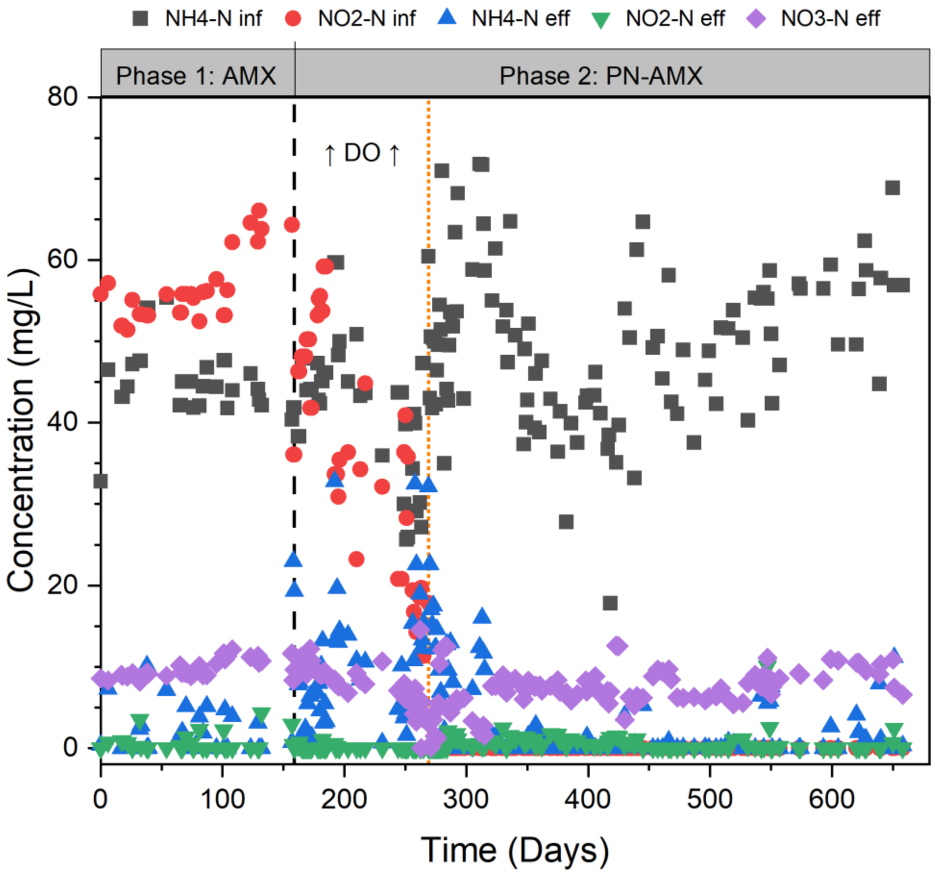
Partial nitritation/marine anammox granules cultivated with Red Sea water







Performance of the granular PN/MA reactor



<u>Phase 1:</u>

[NH_4-N] inf = 46.46 ± 5.67 (mg L^{-1})

[NO_2-N] inf = 54.11 ± 1.69 (mg L^{-1})

[NH_4-N] eff = 2.35 ± 3.16 (mg L^{-1})

[NO_2-N] eff = 0.53 ± 0.87 (mg L^{-1})

[NO_3-N] eff = 9.00 ± 0.45 (mg L^{-1})

[NRR] = 0.3908 ± 0.09 (kgN $m^{-3}d^{-1}$)

<u>Phase 2:</u>

[NH_4-N] inf = 46.99 ± 5.67 (mg L^{-1})

[NH_4-N] eff = 5.44 ± 7.24 (mg L^{-1})

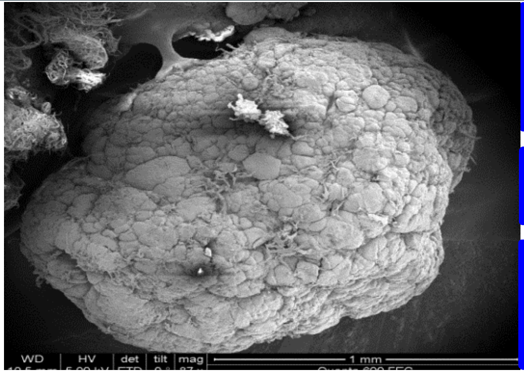
[NO_2-N] eff = 0.49 ± 1.07 (mg L^{-1})

[NO_3-N] eff = 7.64 ± 2.73 (mg L^{-1})

[NRR] = 0.51 ± 0.37 (kgN $m^{-3}d^{-1}$)

- *Ca*. Scalindua scaelec01 a marine anammox strain was dominant in phase 1 (63%) and 2 (32%).
- Members of the genus *Nitrosomonas* (5 species) were dominant in phase 2 (14%).

3. Aerobic granular sludge



Theme 1: Integrating AGS with gravity driven membrane for energy-efficient decentralized WWT and reuse

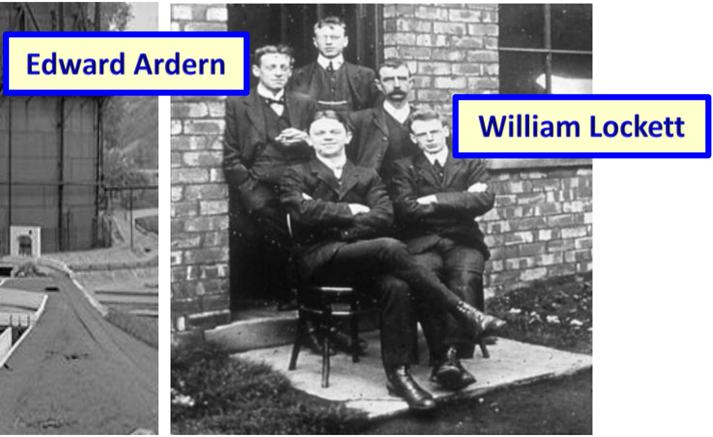
Theme 2: Understanding the assembly mechanism of aerobic granules

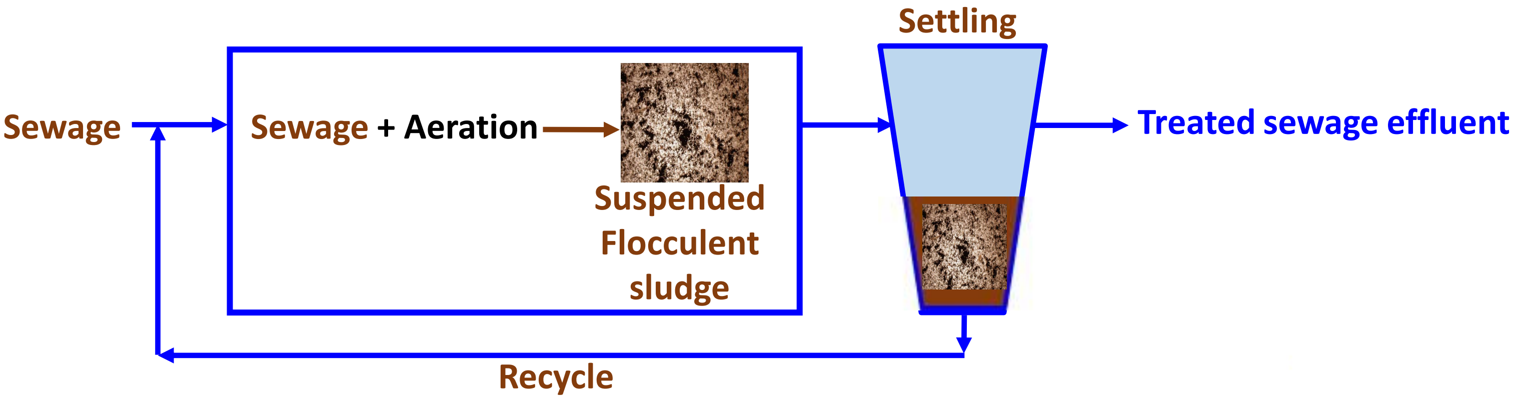
Theme 3: Expanding the application of AGS for industrial wastewater treatment

Water Research, 2017, 124, 702-712; ***Frontiers in Microbiology***, 2018, 9:479; ***Environmental Science and Technology***, 2019, 53, 8291-8301; ***ACS EST Water***, 2023, 3, 2681-2690

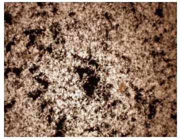
Wastewater treatment based on activated sludge – 110 years old (1914)

The Rellinghausen Wastewater Treatment Plant
First full-scale wastewater treatment plant based on activated sludge on the European continent



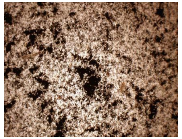


Activated sludge process has evolved, but slowly, since 1914



1914

CAS
Conventional Activated Sludge

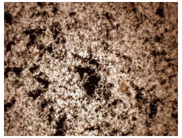


1980

SBR
Sequential Batch Reactor

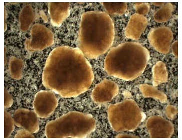
1980s

MBBR
Moving Bed Biofilm Reactor



1990

MBR
Membrane Bioreactor



2011

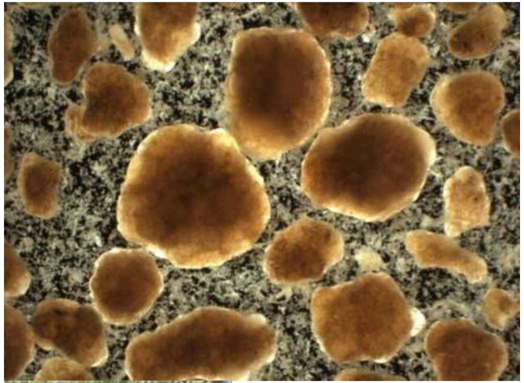
AGS
Aerobic Granular Sludge

~100 years

CAS → **AGS**

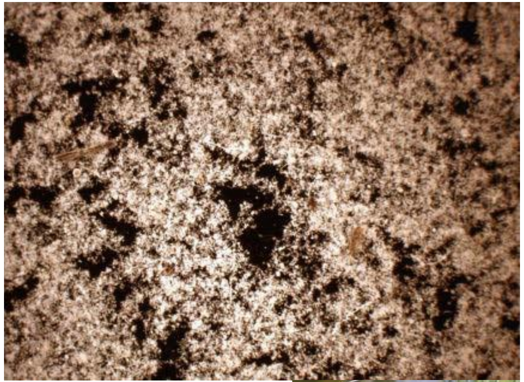
Aerobic granular sludge vs. conventional activated sludge

AGS



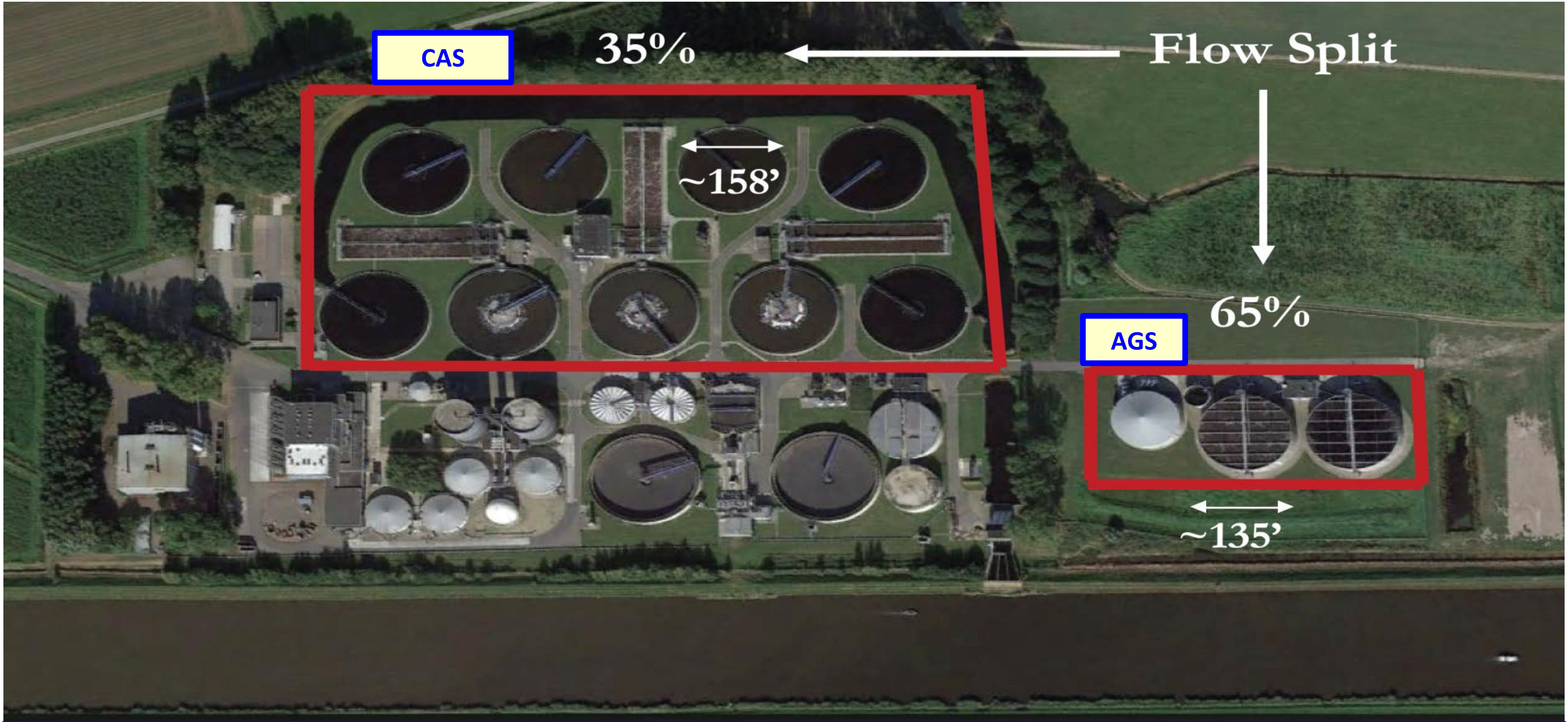
- **Granules (> 0.2 mm)**
- **Fast settling**
- **MLSS: > 8 g/L**

CAS



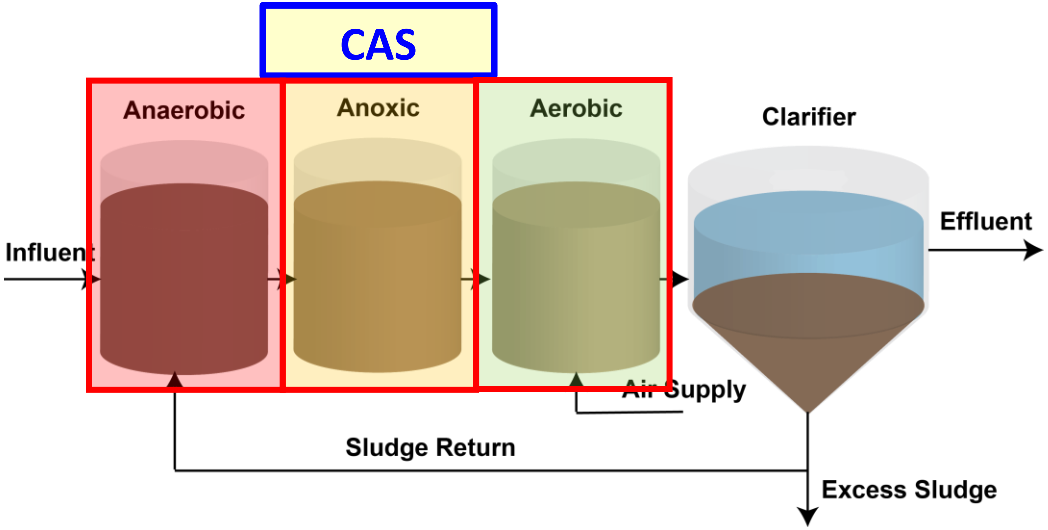
- **Flocs (~0.2 mm)**
- **Slow settling**
- **MLSS: 3 g/L**

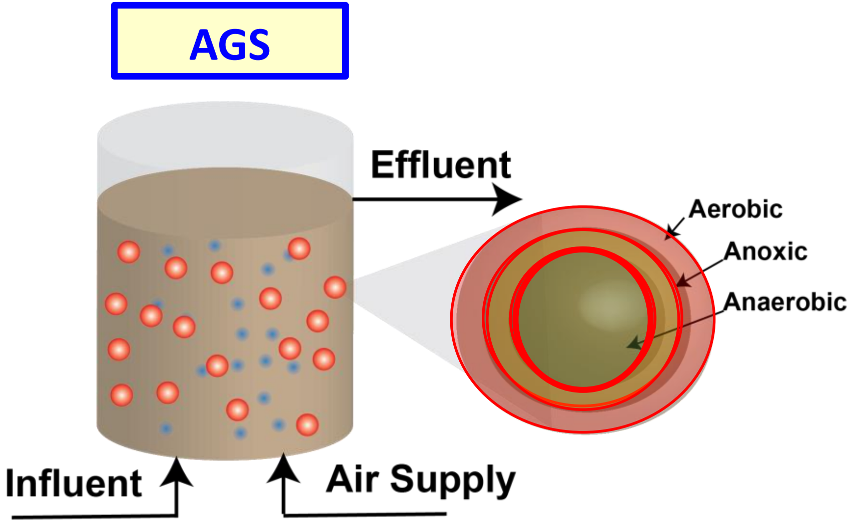
Garmerwolde centralized WWTP in The Netherlands (CAS vs. AGS)

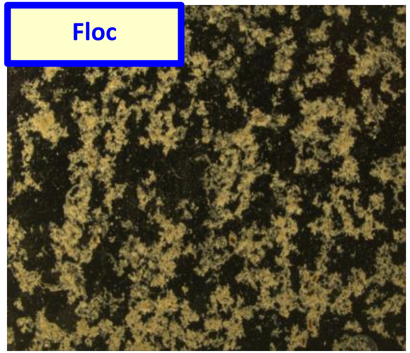


AGS: 75% reduction in footprint

Organics and nutrients (N and P) removal: CAS vs. AGS

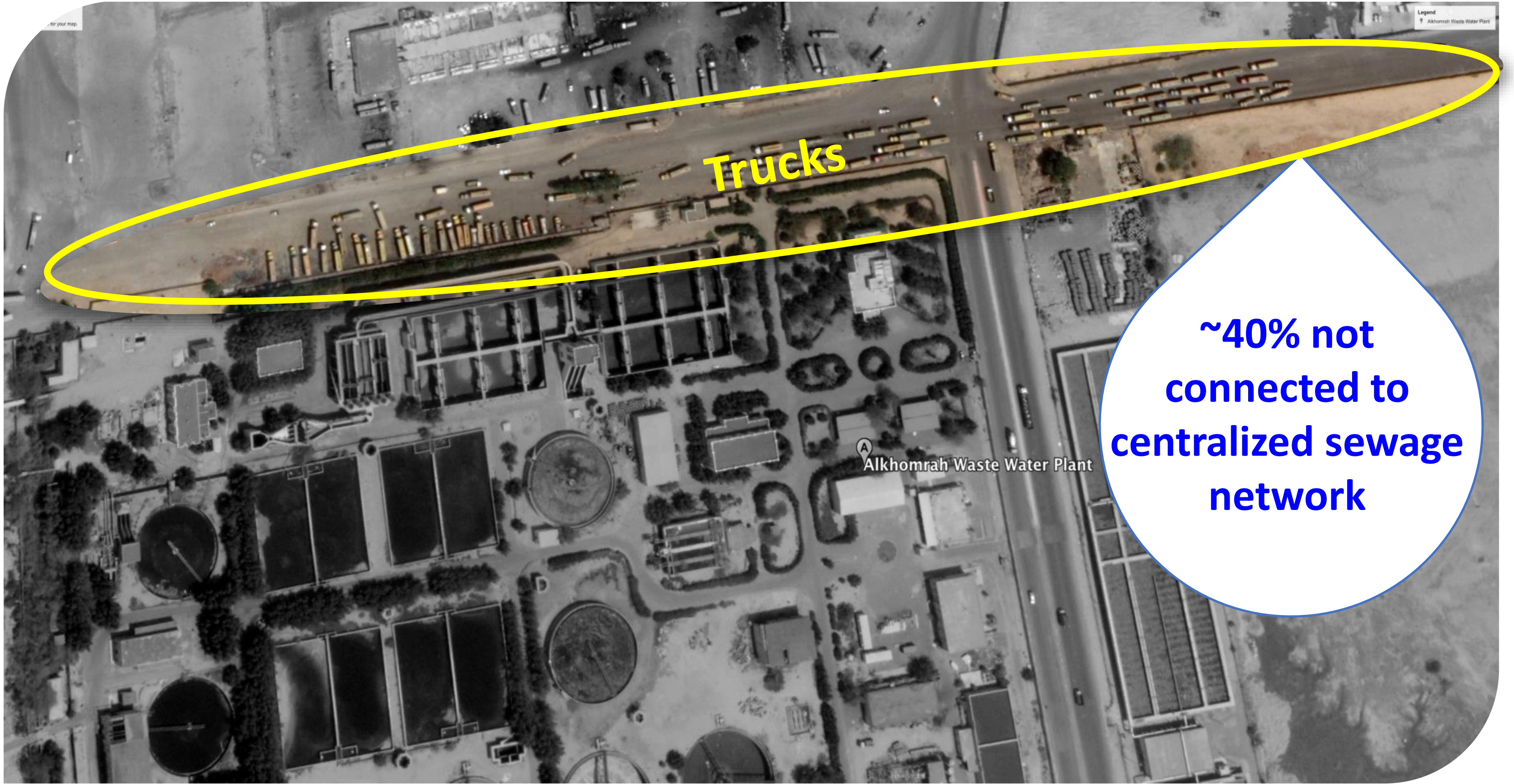






- Simultaneous removal of organics and nutrients (N, P)
- Reduction in capital & operational costs (less mechanical equipment, less pumping, less aeration)
- Significant energy savings

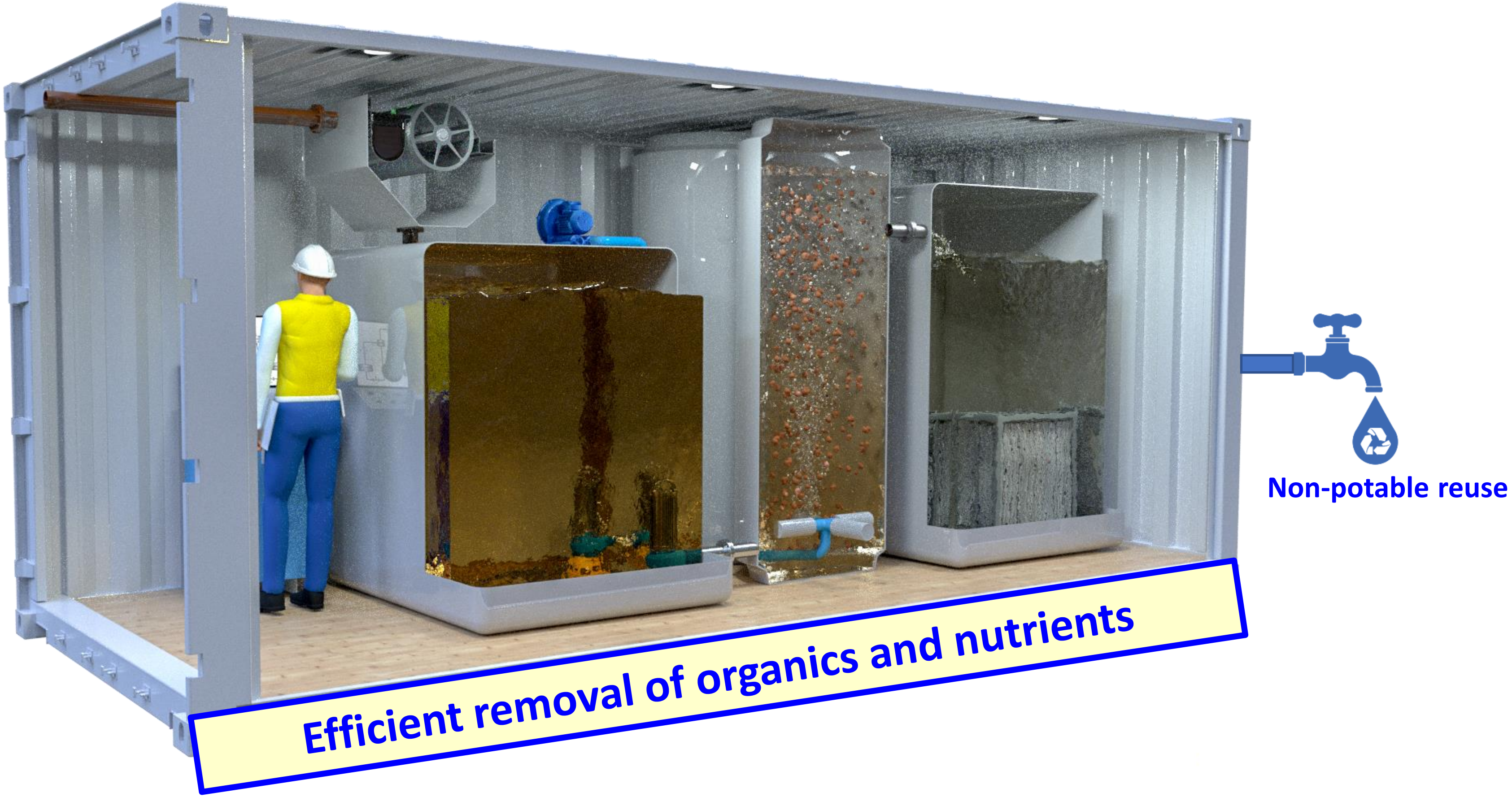
Centralized WWTP in Jeddah based on conventional activated sludge



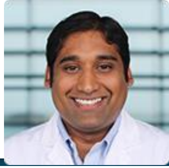
Existing centralized WWTP based on conventional activated sludge are not designed to achieve efficient biological nutrient removal

MEWA devised Saudi National Water Strategy: 100% WWT and increase reuse of TSE from 25% (2022) to 70% (2030)

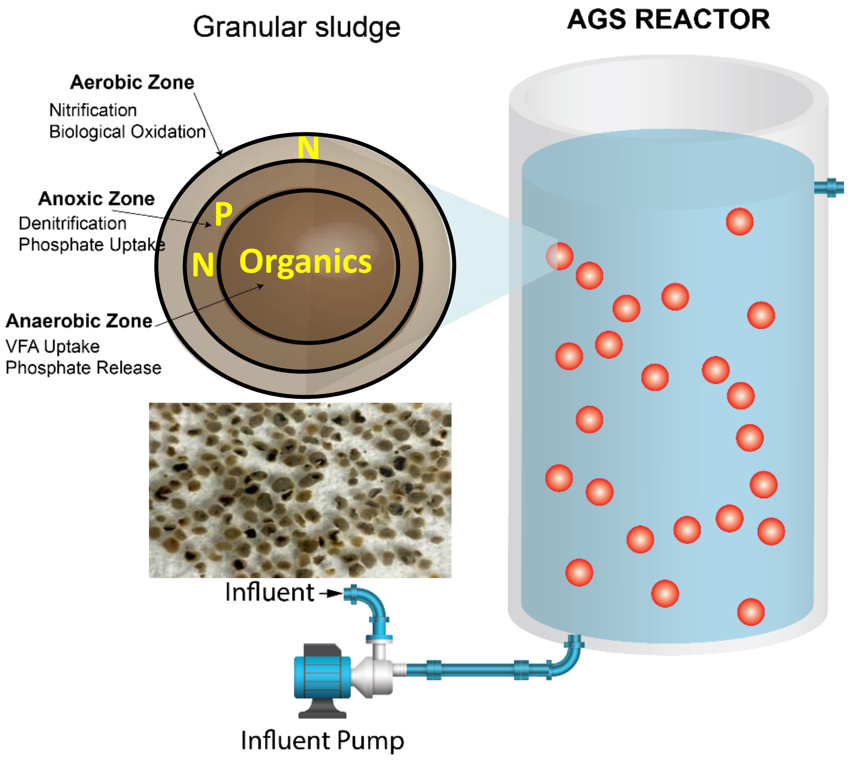
Solution – A decentralized wastewater treatment and direct reuse technology based on aerobic granular sludge: serving ~1000-2000 PE



Integrating AGS with gravity-driven membrane (GDM): energy efficient decentralized WWT and direct reuse

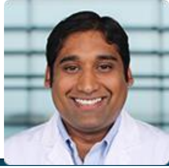


Dr. Muhammad Ali

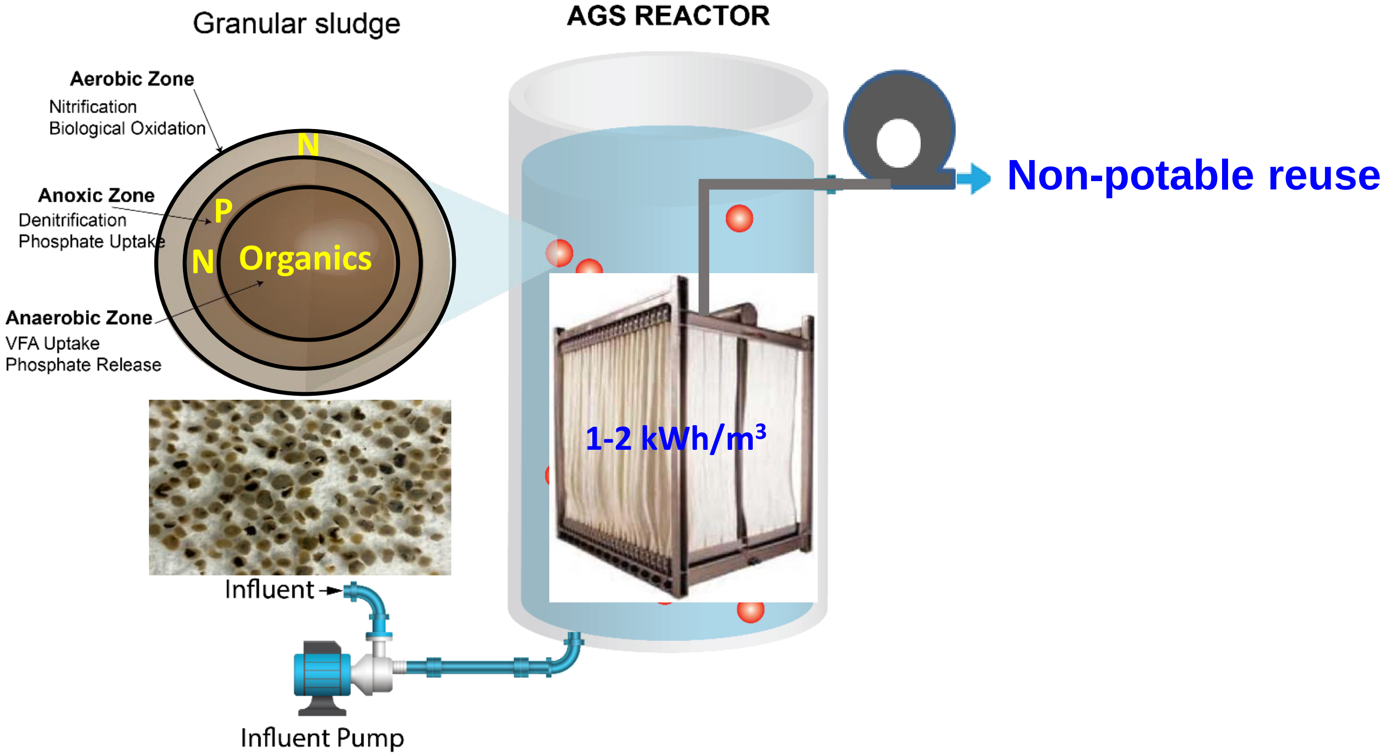


Patent: WO 2020/104944 A1

Integrating AGS with gravity-driven membrane (GDM): energy efficient decentralized WWT and direct reuse

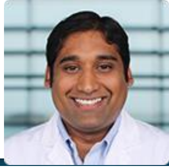


Dr. Muhammad Ali

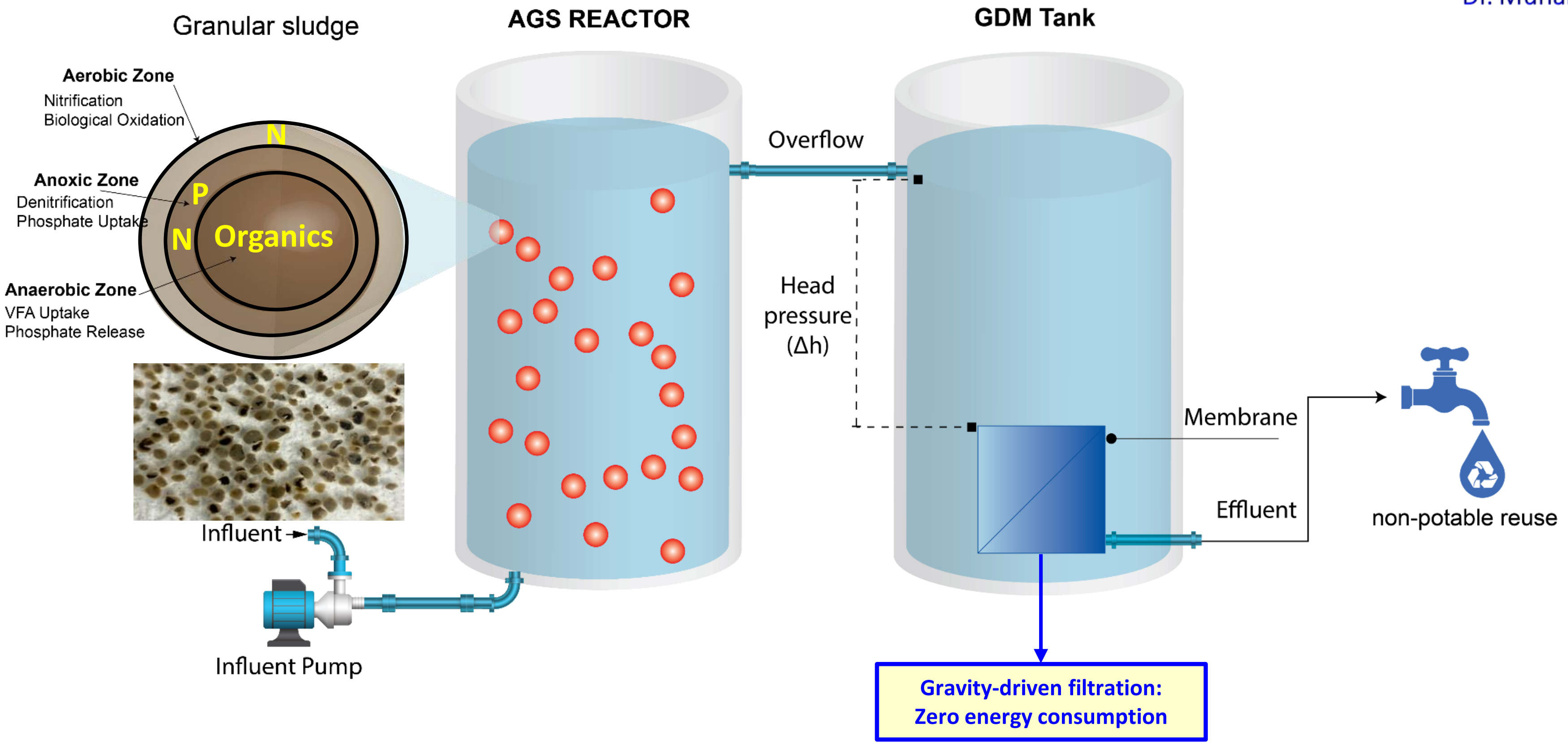


Patent: WO 2020/104944 A1

Integrating AGS with gravity-driven membrane (GDM): energy efficient decentralized WWT and direct reuse



Dr. Muhammad Ali



Patent: WO 2020/104944 A1

Pilot-scale AGS-GDM vs. full-scale AeMBR based on AS

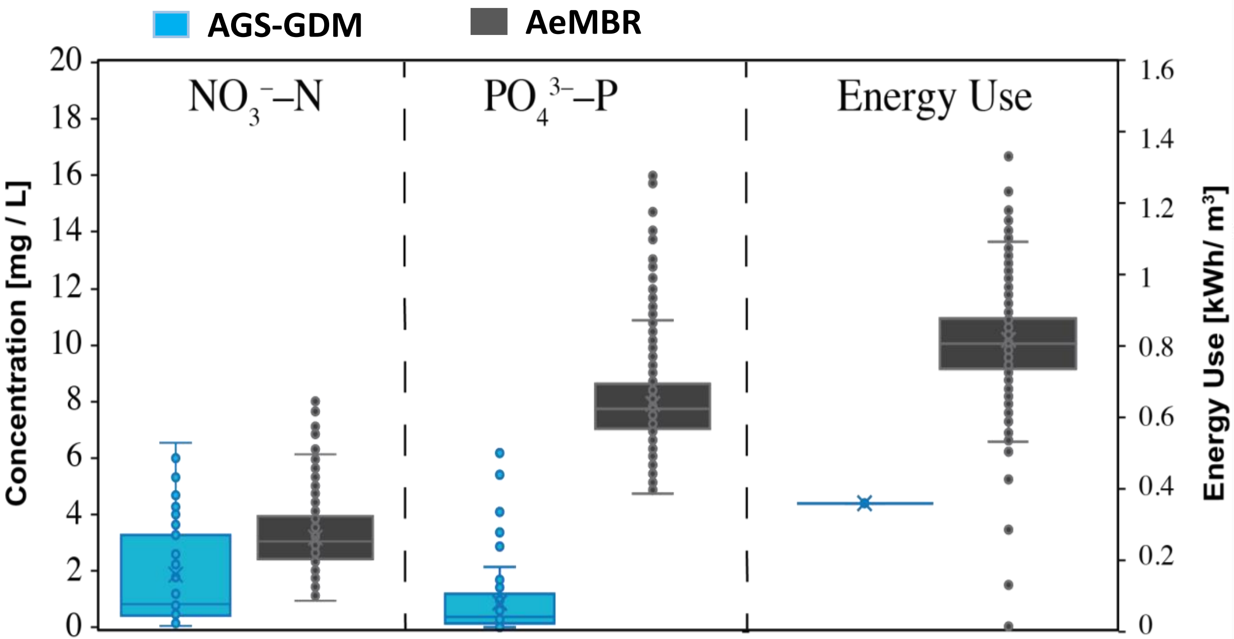
AGS-GDM

100 L/d

KAUST aerobic membrane bioreactor (AeMBR)

4,000 m³/d

Performance of AGS-GDM vs. AeMBR



- **Better treated water quality of AGS-GDM compared to AeMBR with 80% less N and P**
- **Energy consumption for aeration was 56% lower in AGS-GDM than AeMBR**

ACS EST Water, 2023, 3, 2681-2690

Technology readiness level

Lab-scale (12 L/day)
TRL 1-4

Pilot-scale (100 L/day)
TRL 5-6

Full-scale (100 m^3/day)
TRL 8

2018 — Lab Prototype (12 L/day)

2019 — Pilot Plant (140 L/day)

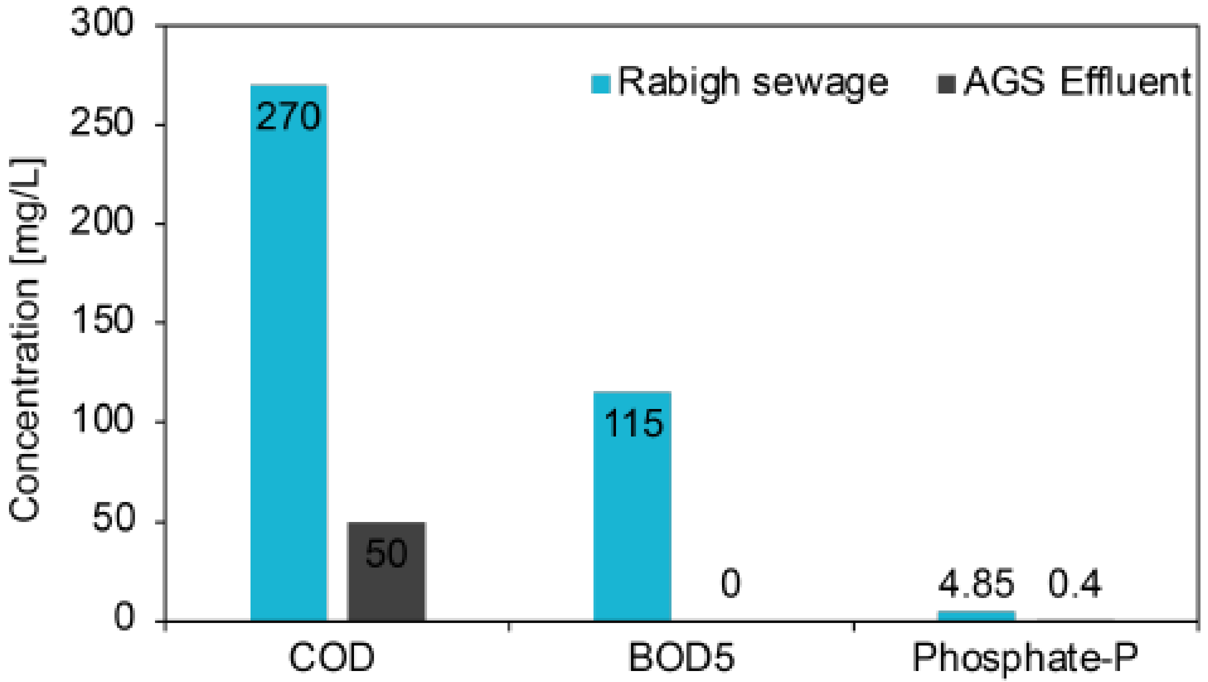
2020 — Testing Pilot Plant

2022 — Full-scale Unit (100 m³/day)

2023 — Operation in Rabigh

First full-scale decentralized wastewater treatment and recycle unit based on AGS-GDM system at the National Water Company WWTP in Rabigh

Performance of full-scale unit



Collaborators: KAUST and international


Prof. Suzana Nunes
KAUST


Prof. Zhiping Lai
KAUST


Prof. Peng Wang
KAUST


Prof. Pedro Da Costa
KAUST


Prof. Daniele Daffonchio
KAUST


Prof. Sigurdur Thoroddsen
KAUST


Prof. Mike Jetten
Radboud University


Prof. Laura van niftric
Radboud University

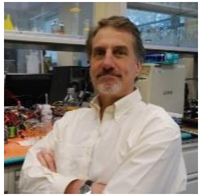

Prof. Mads Albertsen
Aalborg University


Dr. Deepk Pant
VITO, Belgium


Prof. Korneel Rabaey
Ghent University


Prof. Donal Leech
NUI Galway


Prof. Jeffrey Gralnick
University of Minnesota - Twin Cities


Prof. Bruce Logan
Pennsylvania State University


Prof. Mutasem El Fadel
American University of Beirut

Environmental Biotechnology Group