



➤ **Electro-bio-remediation of wastewater**

Manage the redox conditions of biodegradation

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> Output

- **Microbial respirations**
- **Microbial fuel cell**
- **Sediment microbial fuel cell in river**
- **Electrochemical control of biodegradation processes**
- **Some results at lab and pilot scales**
- **Perspectives & questions**



➤ Once upon a time, a very long time ago

More than 2.45 Ga years ago
Atmosphere without O₂ → No aerobic life
Anaerobic bacteria rule the Earth

All living organisms Breathe stones

Metal- and **Sulphate-reducing bacteria**
breathe minerals

Involving electron transfers to
solid terminal electron acceptors (stone surfaces)



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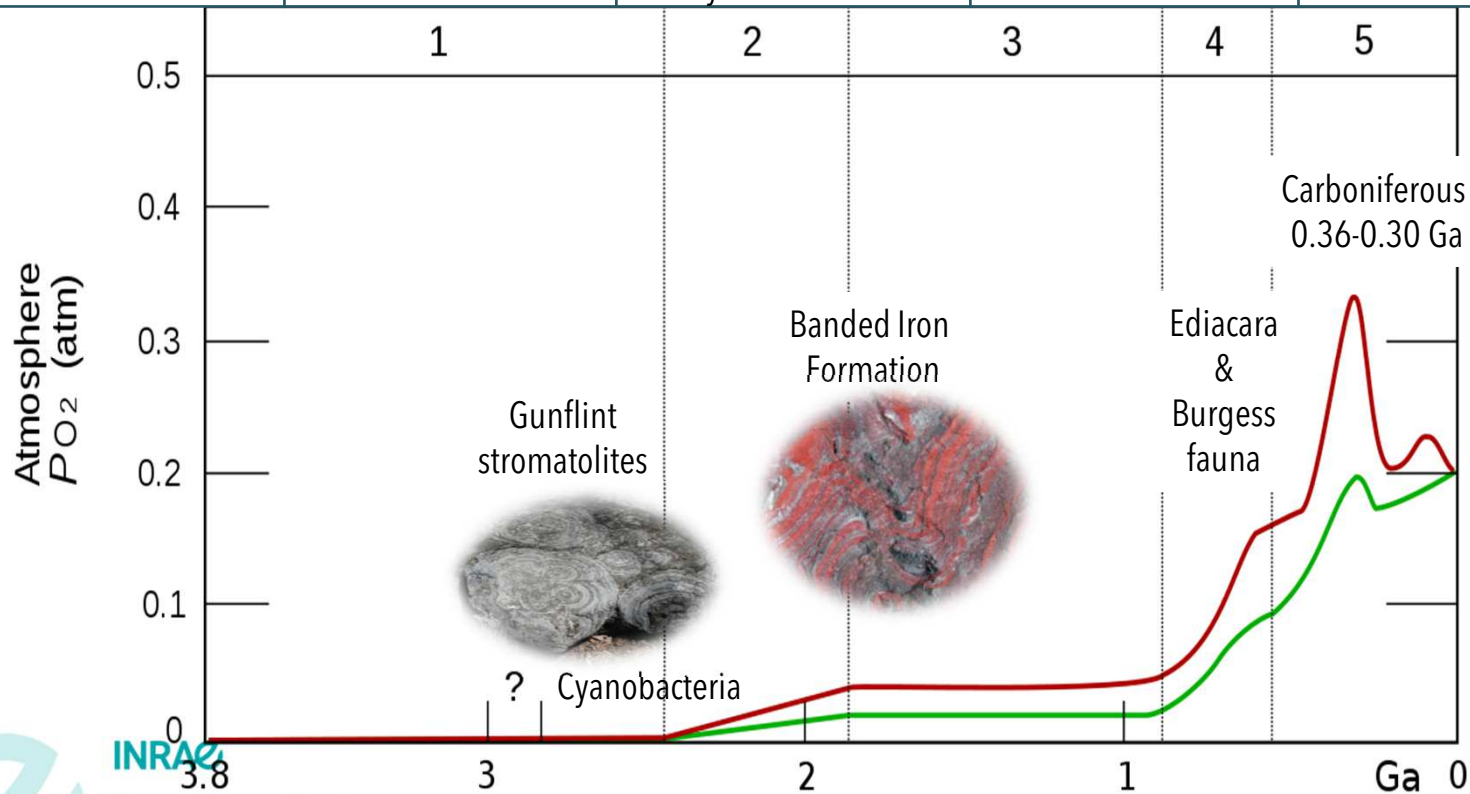
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➤ The Great Oxidation Event

A new microbe produces oxygen (a highly toxic gas)

Stage 1	Stage 2	Stage 3	Stage 4	Stage 5
3.85–2.45 Ga Anoxic stage no O ₂ in the atmosphere, nor in oceans	2.45–1.85 Ga O ₂ rising to 0.02 - 0.04 atm, but absorbed in oceans	1.85–0.85 Ga O ₂ starts to gas out of the oceans, but is absorbed by land surfaces	0.85–0.54 Ga anoxic & euxinic conditions prevailed in the shallow oceans	0.54 Ga - present All O ₂ sinks filled; O ₂ accumulates in atmosphere



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Holland (2006) *Philos. Trans. R. Soc. Lond. B Biol. Sci.*, 361: (1470) 903-915
 Olejarz et al. (2021) *Nat. Commun.*, 12: (1) 3985

Nowadays, these first land-rulers live in hiding, relegated to anoxic, oxygen-deprived biotopes but they are still there



Terminal Electron Acceptors

Fe(III)/Fe(II)

Iron-reducing

Geothermobacter, Geopsychrobacter, Pelobacter carbinolicus, P. acetylenicus, P. venetianus, Desulfuromonadales (Geobacter, Desulfovibrio)

Mn(IV)/Mn(II)

Manganese-reducing

Desulfuromonadales (Geobacter sp., Geoalkalibacter sp., Pelobacter sp., Desulfomonas sp.), Desulfovibrio desulfuricans

NO₃⁻/N₂

Denitrification

Paracoccus denitrificans, E. coli, Pseudomonadaceae (Pseudomonas sp.)

SO₄²⁻/HS⁻

Sulphate-reducing

Desulfuromonadales (Geobacter sp., Geoalkalibacter sp., Pelobacter sp., Desulfovibrio sp., Desulfomonas sp.)

CO₂/CH₄

Methanogens

Methanotherix thermophila

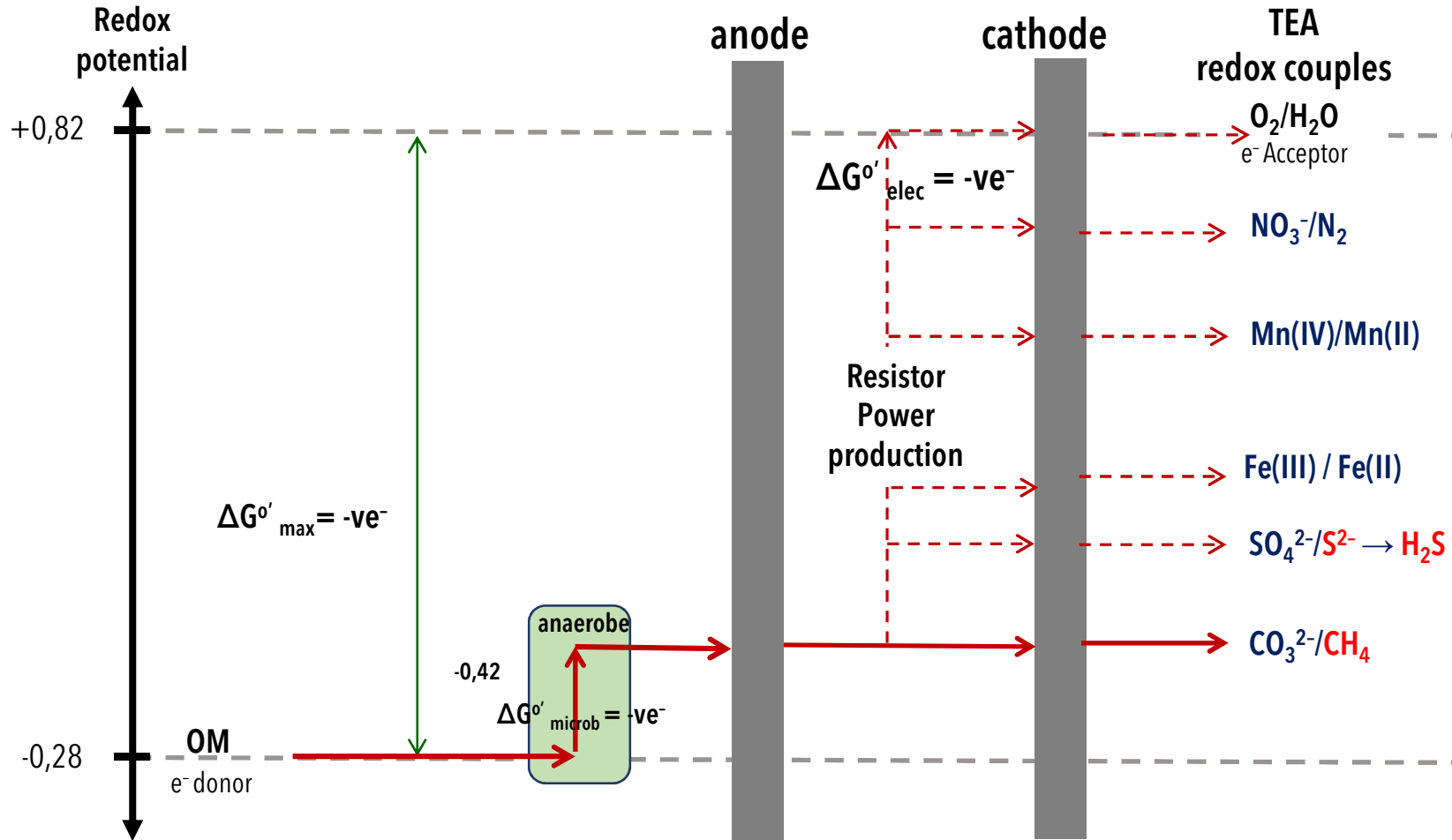


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➤ Microbial electrochemical respirations



Limiting factors

- Masse transfer
- Ohmic lost
- Activation potential



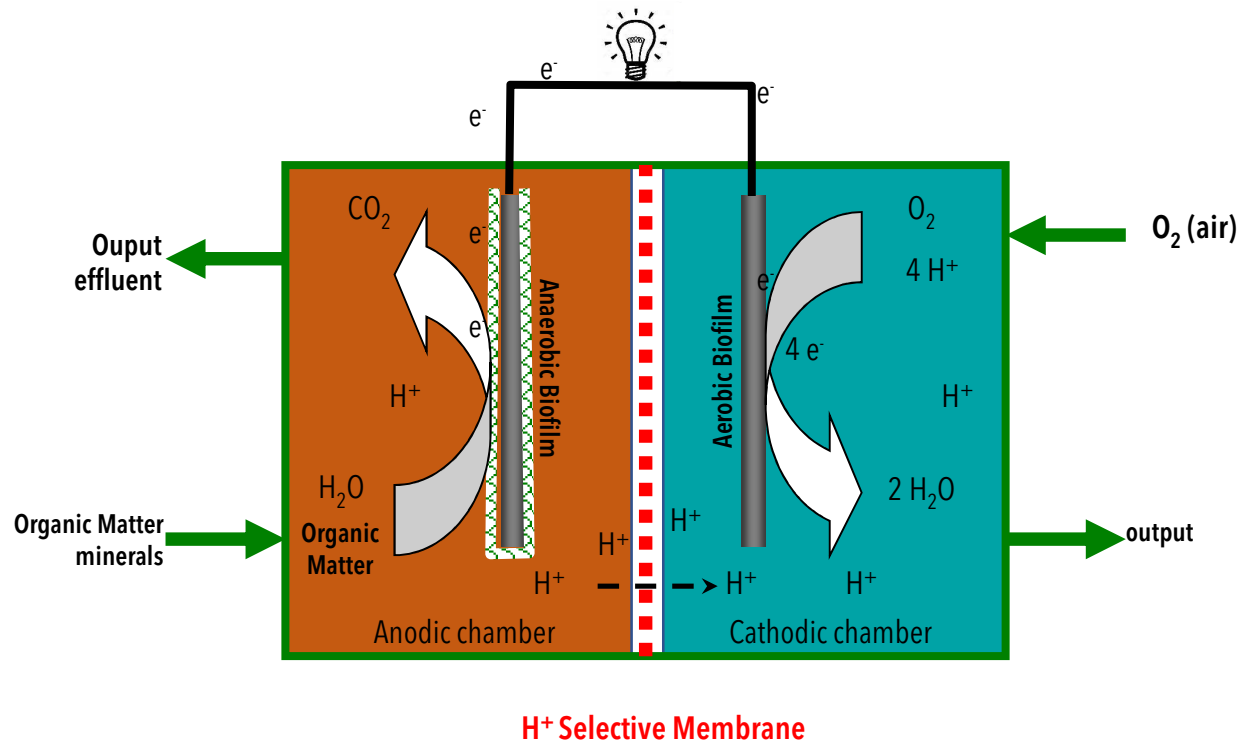
➤ Microbial fuel cell principle

Anoxic Anodic chamber

Anaerobic microorganisms oxidize organic matter and transfer the electrons to the anode

Oxic Cathodic chamber

Electrons are transferred from the cathode to O_2 as terminal electron acceptor



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> Sediment microbial fuel cell principle

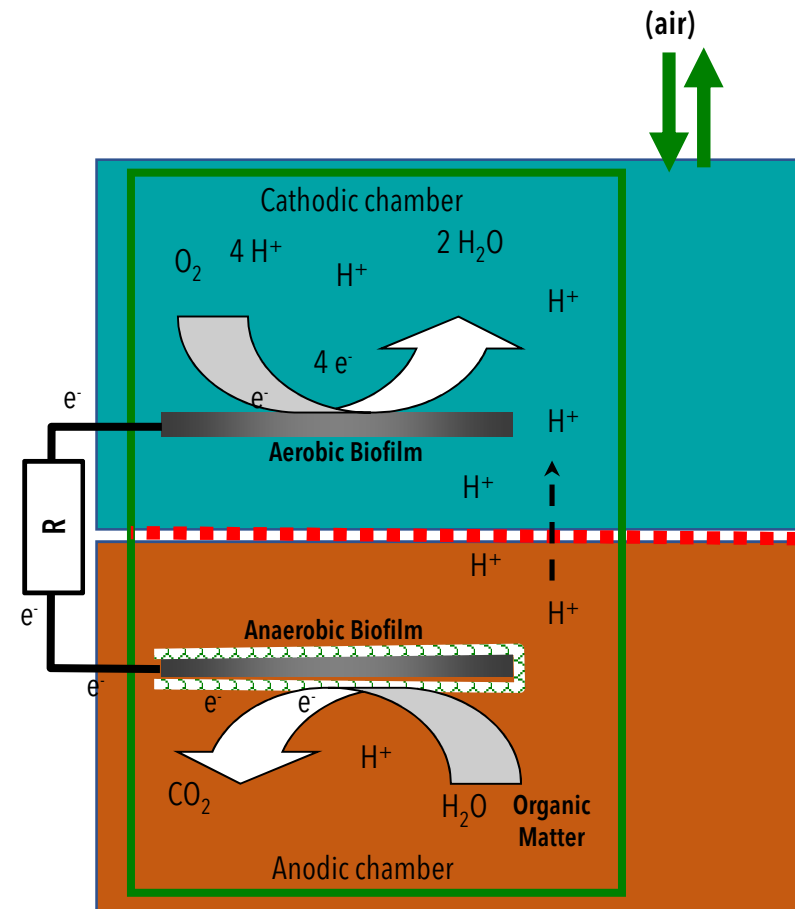
Water = cathodic chamber

Electrons transferred from the cathode to O_2 as terminal electron acceptor

Interface water/sediment = H^+ Selective Membrane

Sediment = anodic chamber

Microorganisms oxidize Organic Matter and transfer their electrons to the anode



➤ **Electro-bioremediation Applications**

Sediment fuel cell in river

Gas control at lab scale

Alexandria pilots



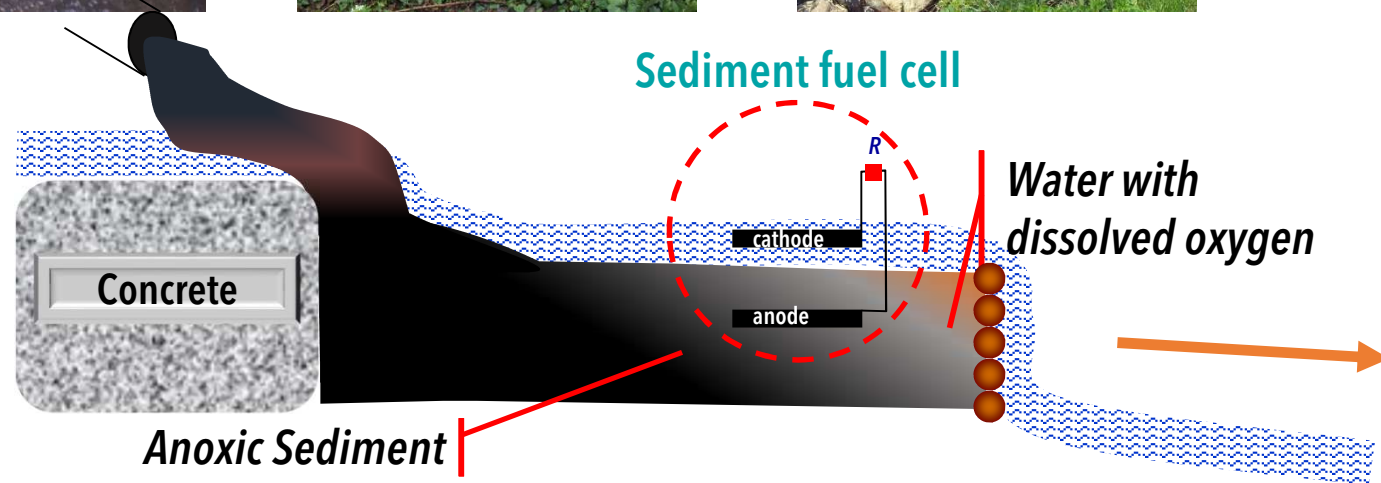
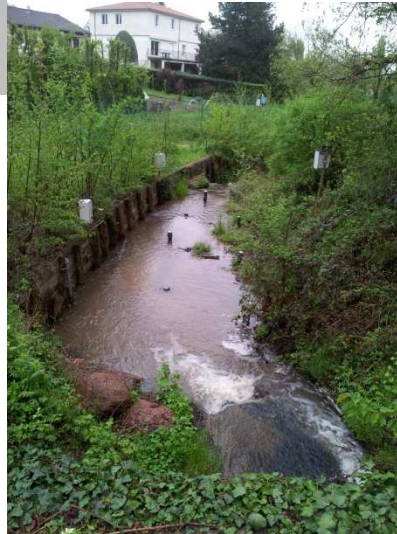
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➤ Sediment fuel cell in porous weir in river

Combined Sewer Overflow
Organic C & N discharge



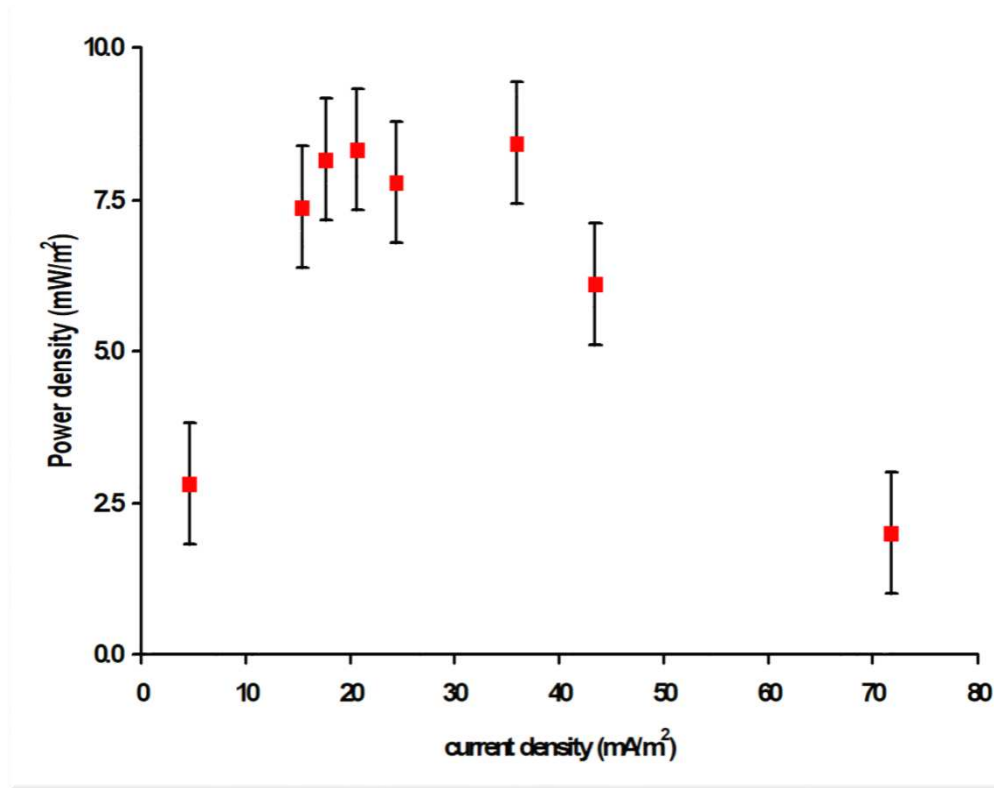
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➤ It's working

But low harvested power



Sediment fuel cell deliver:

Maximal power: ~ 8,8 mW/m²

- Power similar to bench sediment fuel cell in lab
- It was the power delivered by microbial fuel cells 20 years ago (now $\approx 10 \text{ W/m}^2$ reached)

Low power requiring concentration (capacitor) for one-off and decentralised use
e.g. power supply for environmental monitoring micro-sensors



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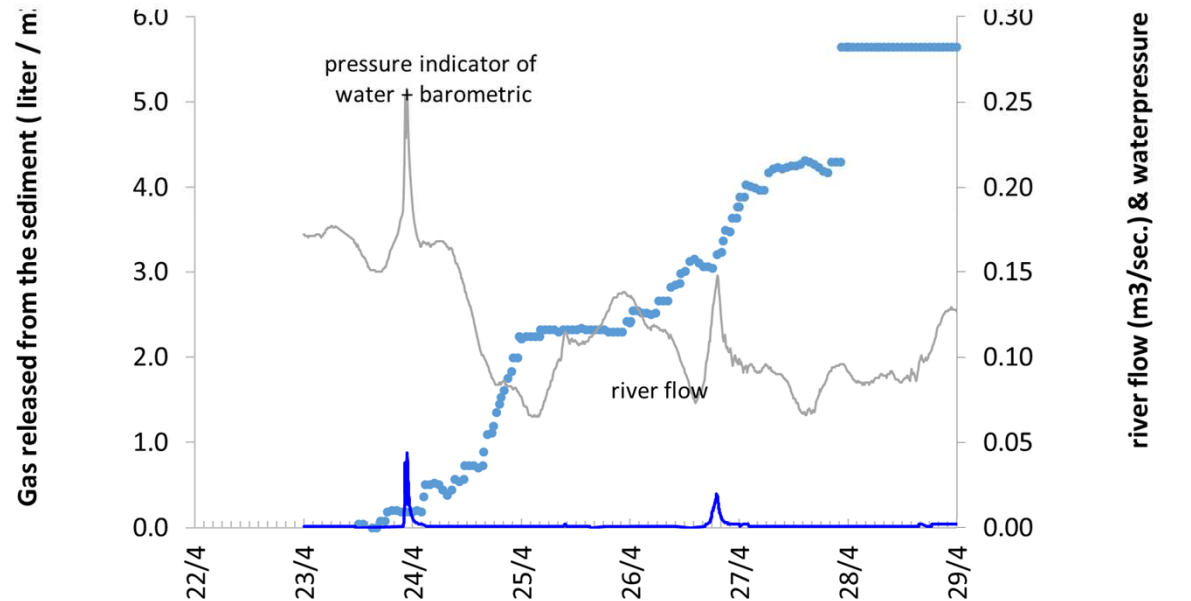
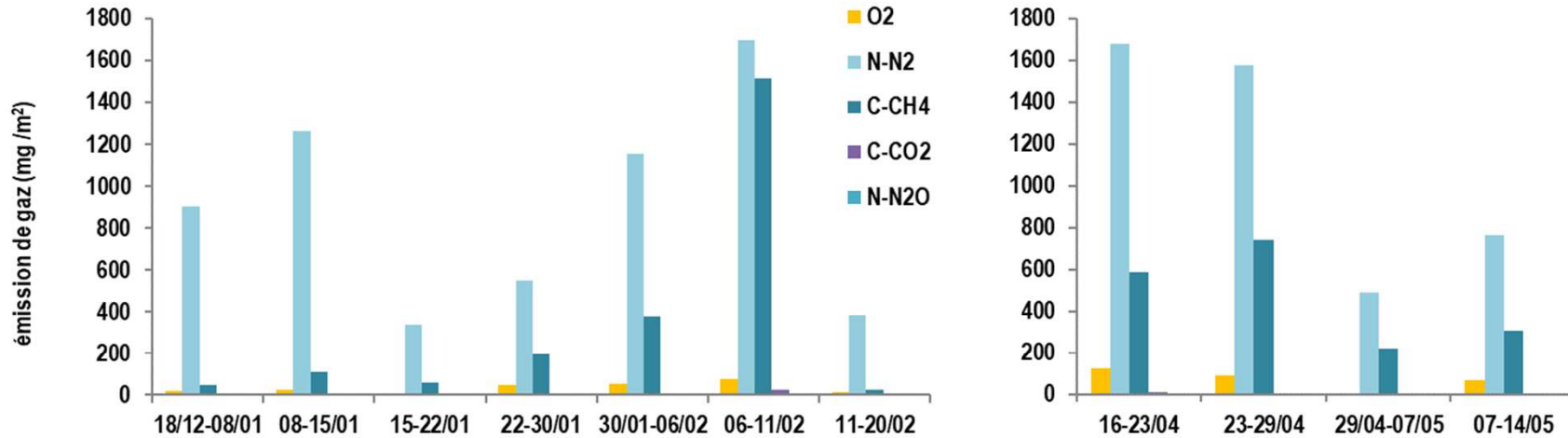
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p. 11

Namour *et al.*, 2014. Sensor. Transduc., 27: 290-294.

➤ Gas analysis results (Chaudanne river)



➤ Principle of electrically directed bioremediation

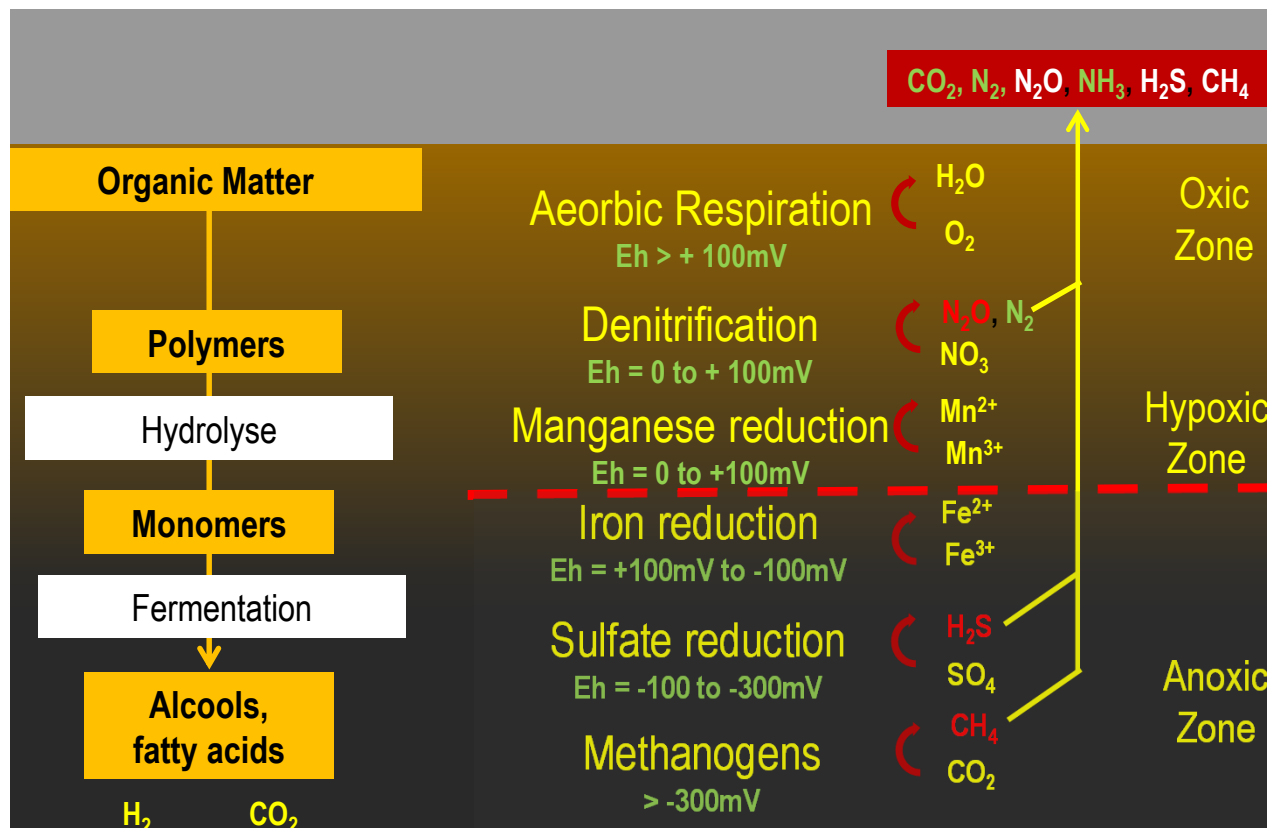
Redox fine-tuning for maximum self-purification
without producing noxious gases: H_2S , CH_4 & N_2O

By creation of a forbidden redox zone

redox potential poised
at -100 mV

Enhance self-purification
Total denitrification
without N_2O emission

No
 H_2S & CH_4
gas production

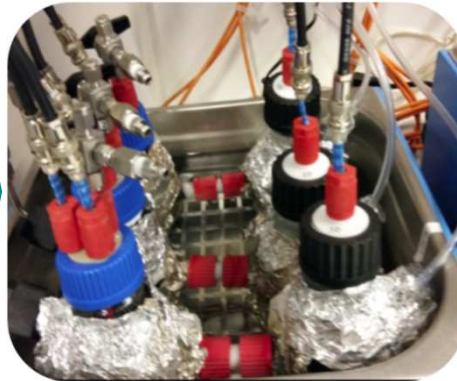
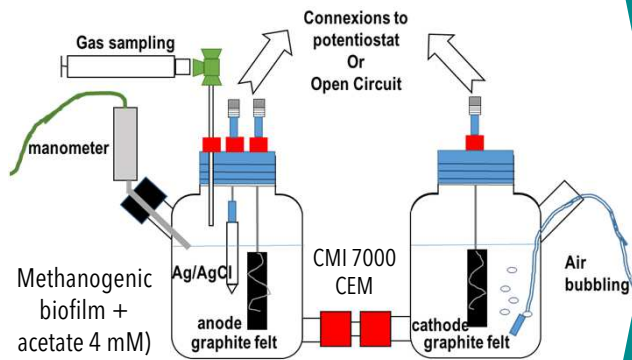


➤ Controlling CH₄ production at the lab-scale

Gastight Microbial Fuel Cell (MFC)
Equipped with pressure sensor and sampling valve

Run in Triplicates
incubated at 31°C for
8 days

MFCs redox potential
poised at 300 mV
(Ag/AgCl)
or open circuit

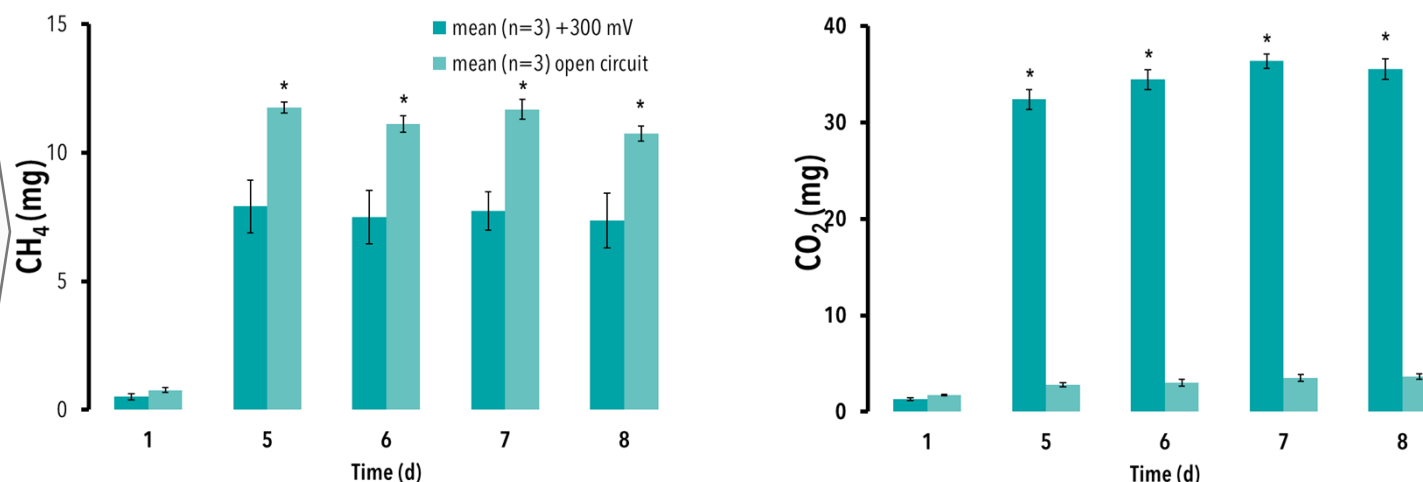


**Gas production is continuously monitored and
daily analysed by GC-MS**



➤ Controlling CH₄ production at the lab-scale

CH₄ and CO₂ generated in circuit poised at 300 mV (Ag/AgCl) and in open circuit



Bars show standard deviation (n = 3); Asterisks show the significant differences (P < 0.05) Between closed and poised at +300 mV circuit and open circuit

Sediment MFCs poised at +300 mV (Ag/AgCl) significantly :

- ↘ CH₄ production by 33%
- ↗ CO₂ production by about an order of magnitude (x 9.8)

Result

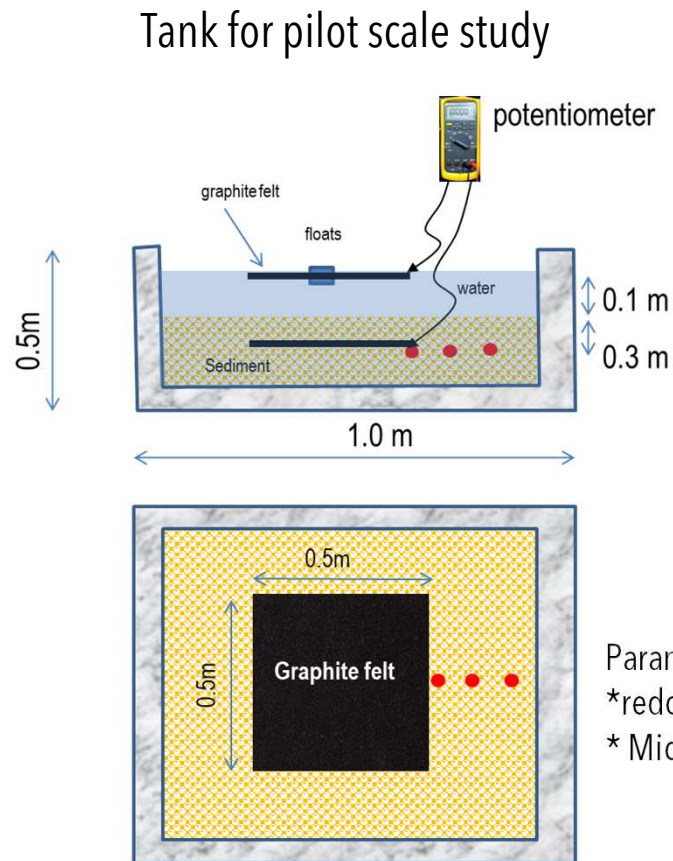
Total "carbon footprint" 23% reduced

Electro-bioremediation could both **reduce greenhouse gas emissions** and **enhance the biodegradation** of organic matter



➤ Alexandria pilot at the NIOF El-Max research station

Installation of electrochemical remediation pilots



connexions



Parameters to measure at points ●:
*redox, pH (weekly monitoring)
* Microbial (sediment sampling : coring)

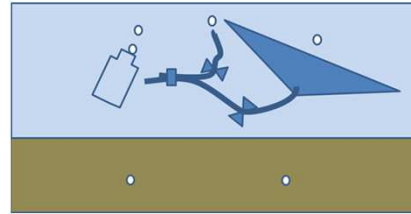


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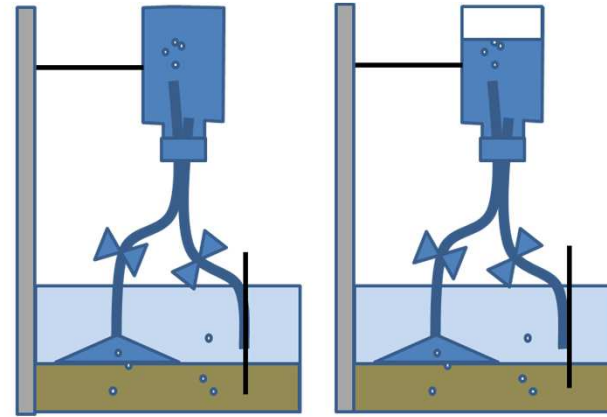
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➤ Gas sampling



set up full of water



gas collecting



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➤ Results from the Alexandria pilots

All starts as expected

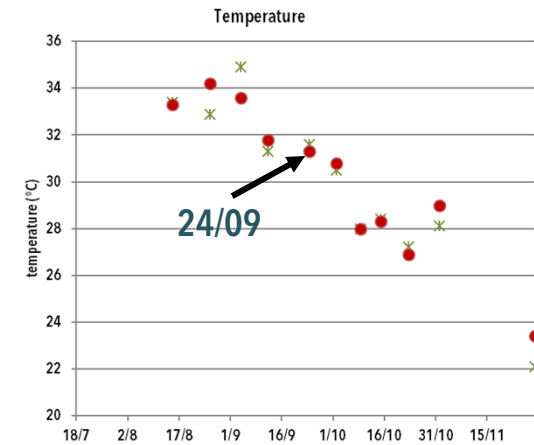
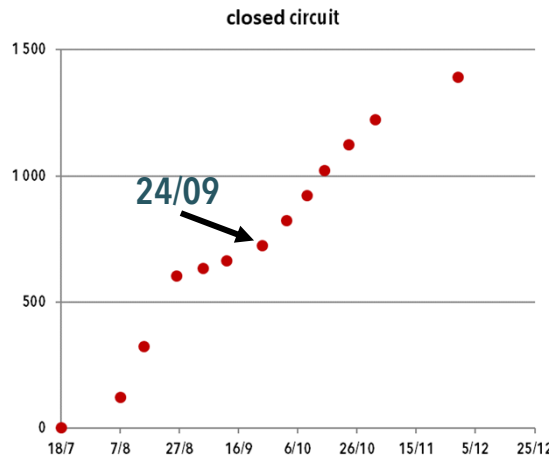
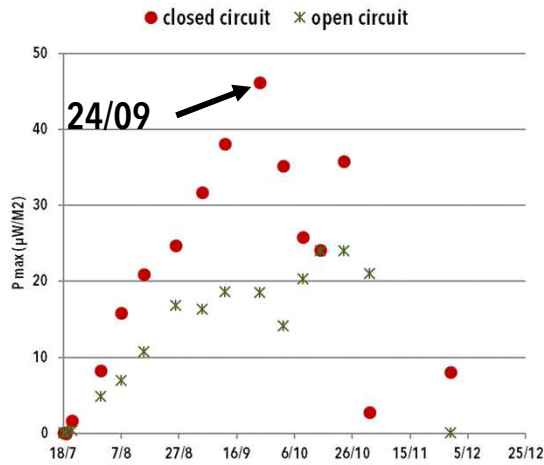
Power production : less power

But, after 24/09 ➔

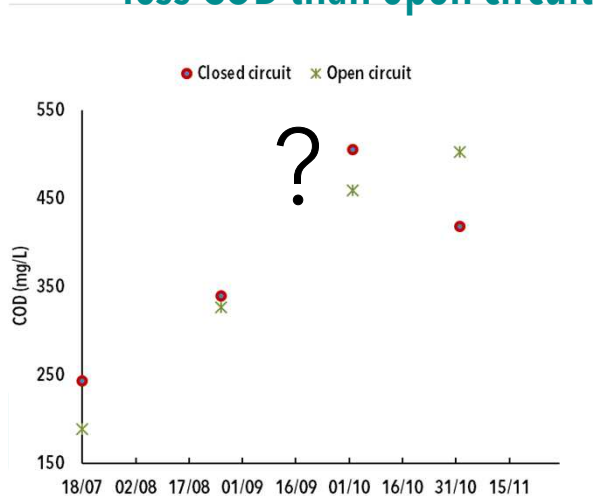
Gas production : more gases

the process changes

Temperature falls <32°C



less COD than open circuit

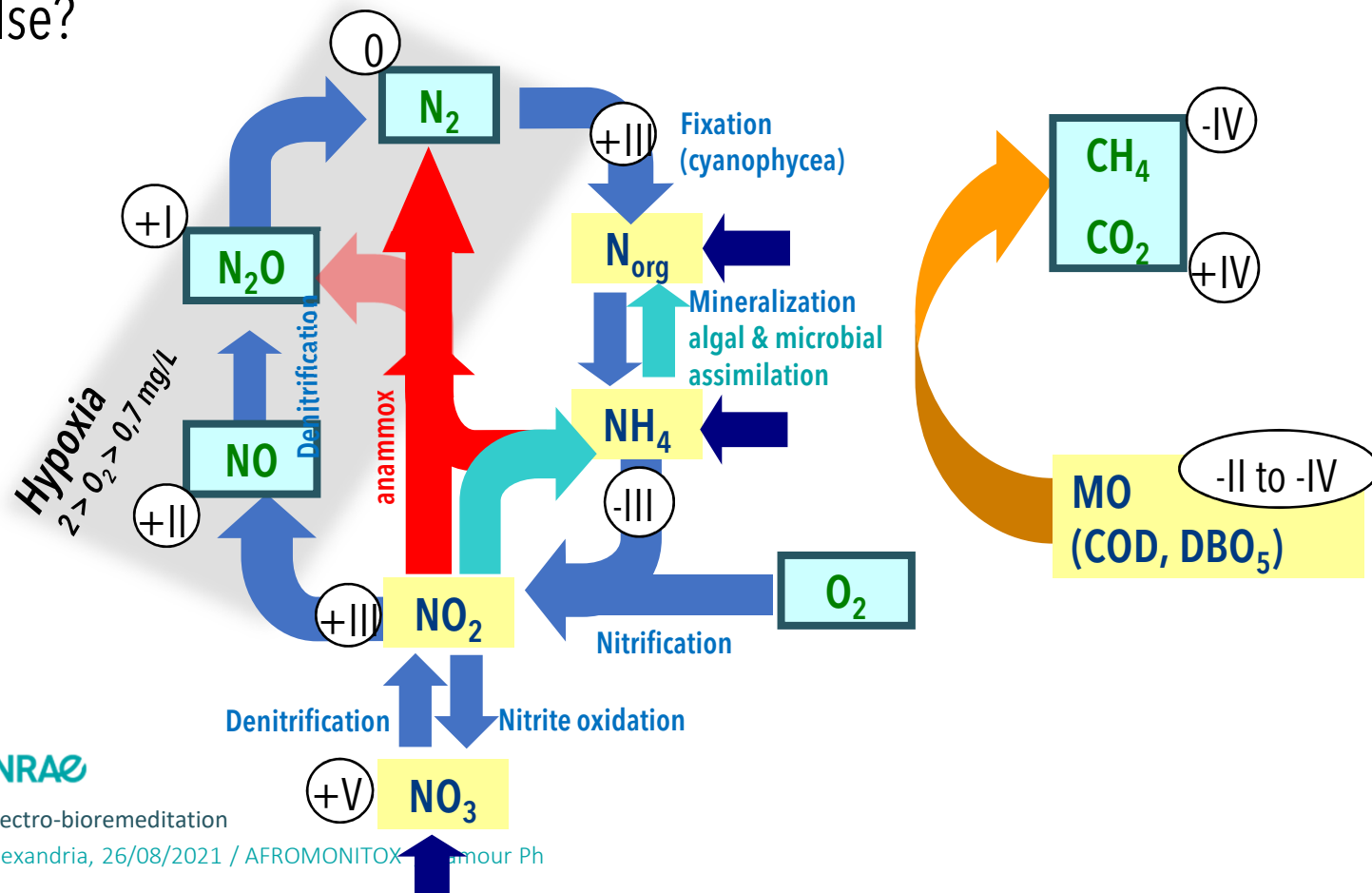


A new metabolic pathway with:

- Electron flux ↘ (change in TEAs?)
- Gas production ↗ (but only pure N₂?)
- Temperature ↘ (change in micro-biocenosis?)
- Maturing / ageing of cathode biofilm ?
-

➤ Solving the Alexandria mystery

- Protocol amendment after 24 September 2018?
- Develop thick biofilm on the cathode?
- Which unexpected microbial consortium lies behind these surprising results?
- Atmospheric pressure drop (to verify) ?
- What else?



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ANR-14-OHRI-0016-01



➤ Thank you for your kind attention

any questions?



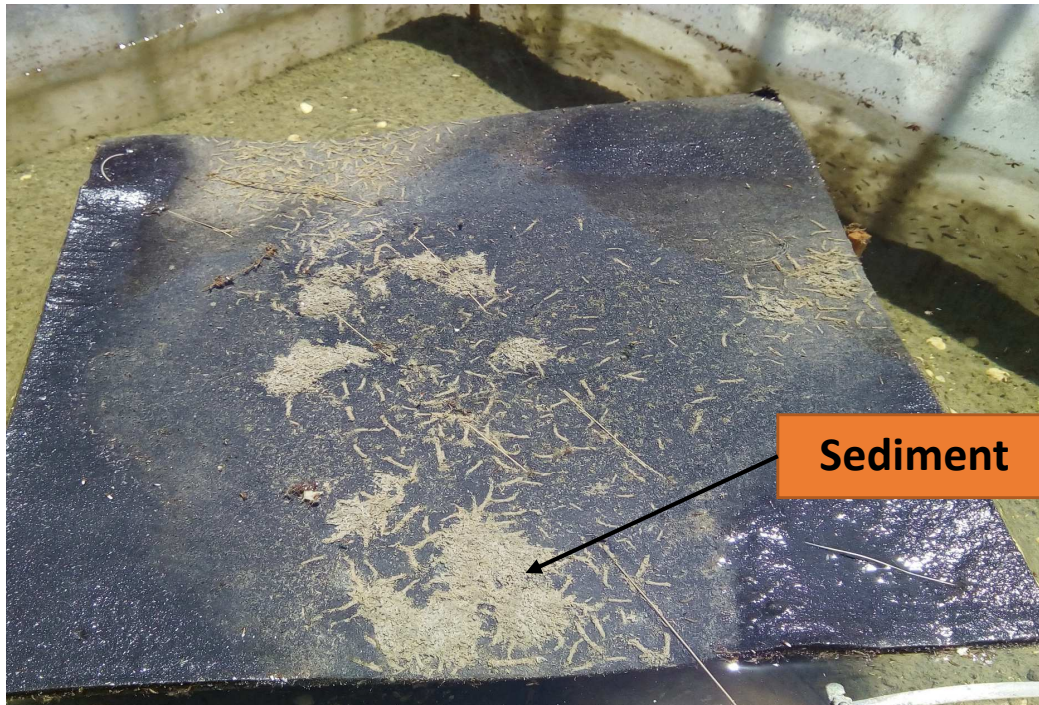
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➤ D₁₃ (31st July, 2018) Week Observations

Sediment existence over the electrode surface (reason?)



Submerged Insects' Larvae



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➤ D₃₉ (26st August, 2018) Week Observations

Two Submerged Cathodes of the open and closed circuits



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➤ D₄₈ (04st September, 2018) Week Observations

Two Submerged Cathodes of the open and closed circuits



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➤ D₅₆ (12th September, 2018) Week Observations

Two Submerged Cathodes of open and closed circuits



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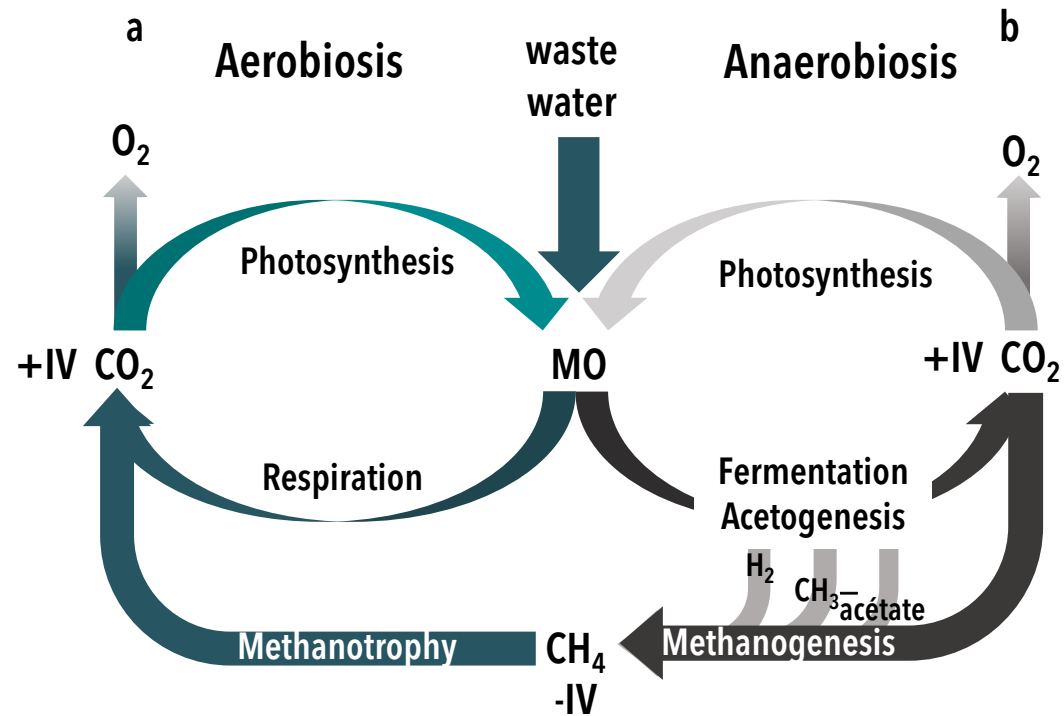
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➤ D₁₃₄ (29th November, 2018) Week Observations

Rain : both tanks filled with rain water



➤ Major pathways of carbon metabolism

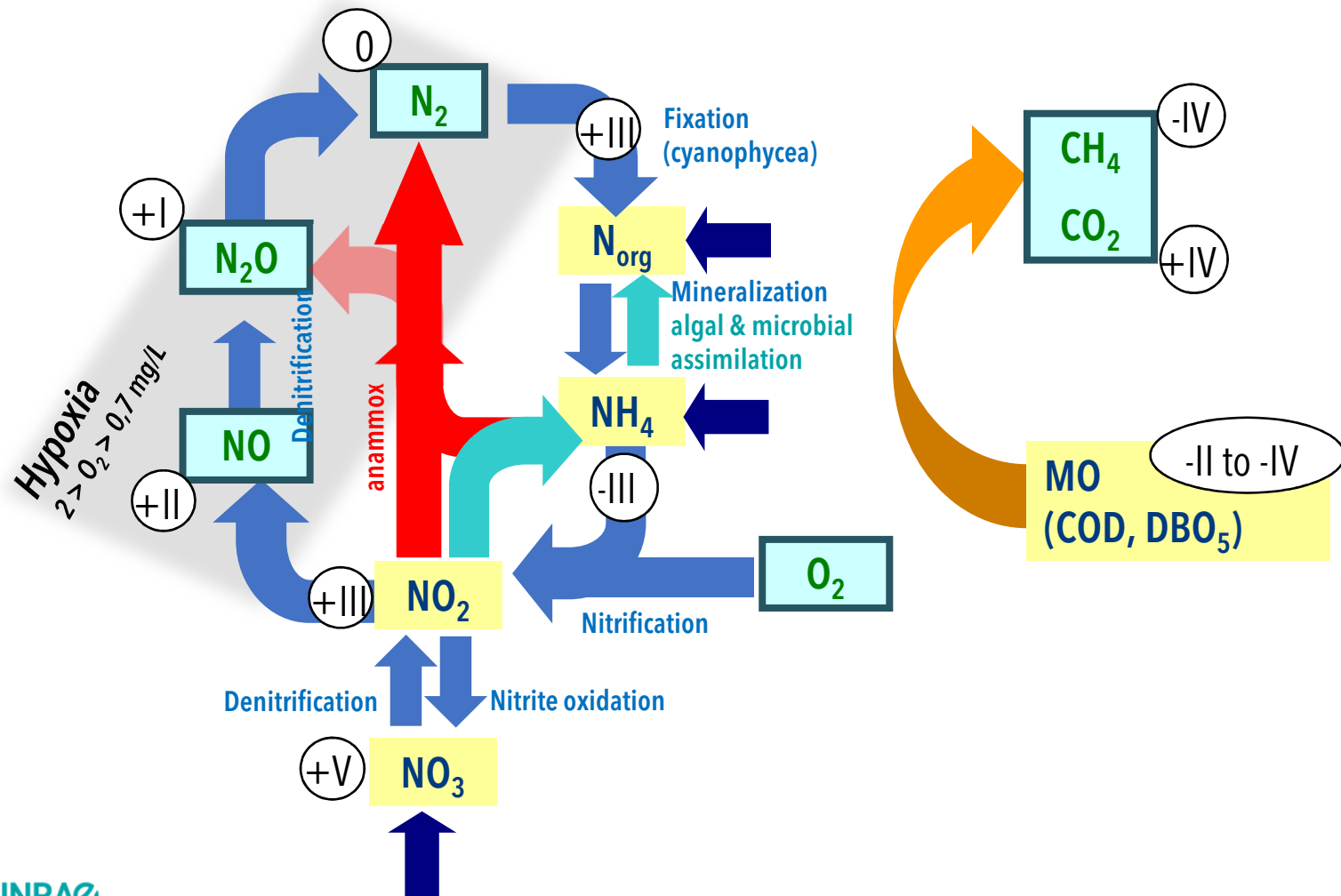


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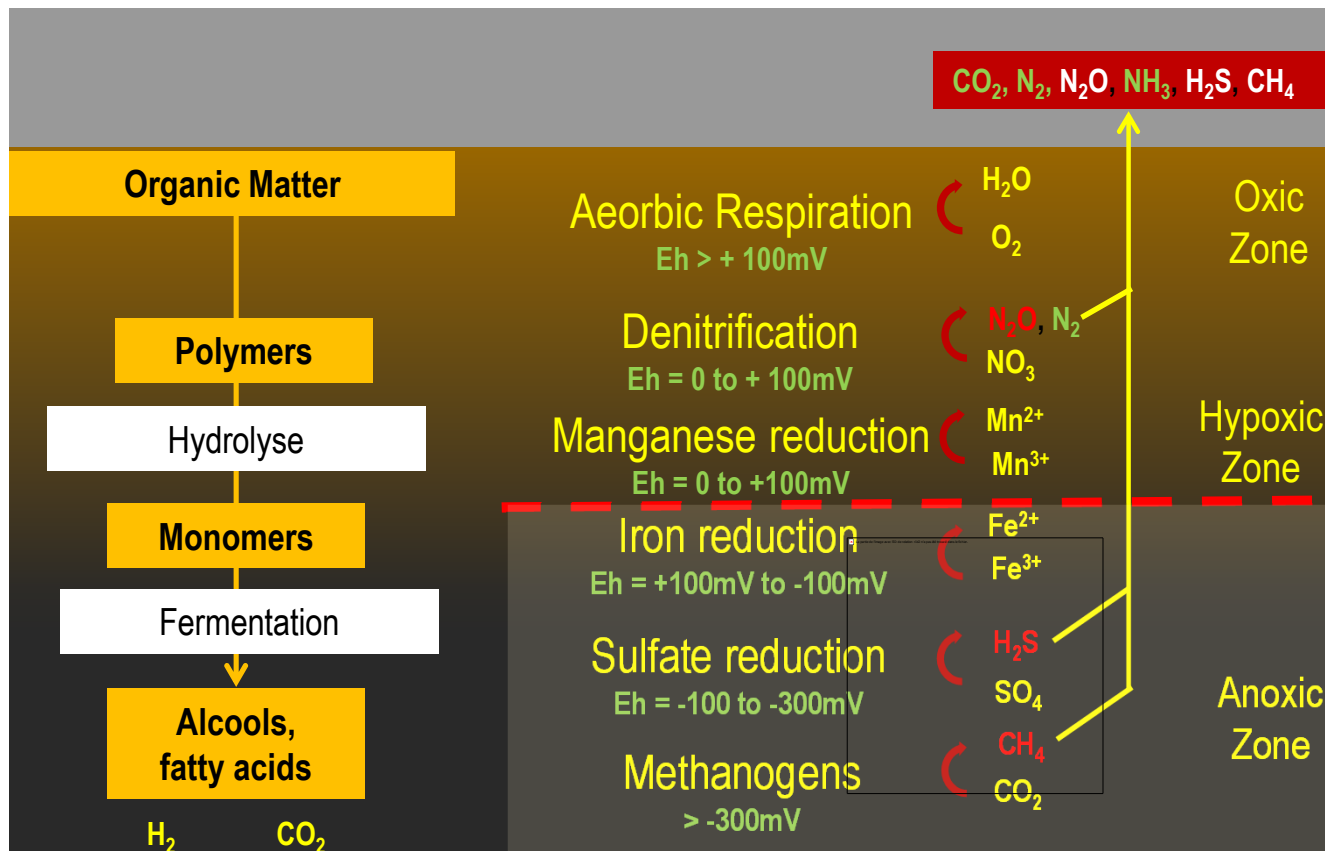
➤ Major pathways of nitrogen metabolism



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