HEI4S3-RM
Building Ecosystem Integration Labs at HEI to foster Smart Specialization and Innovation on Sustainable Raw Materials

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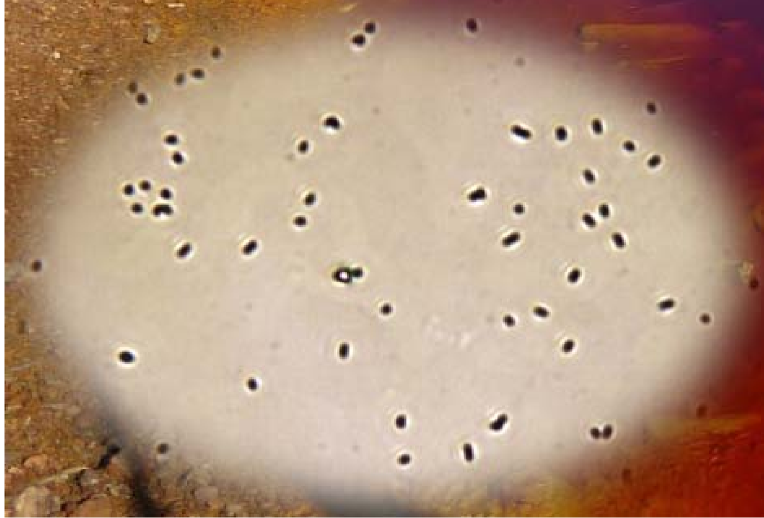
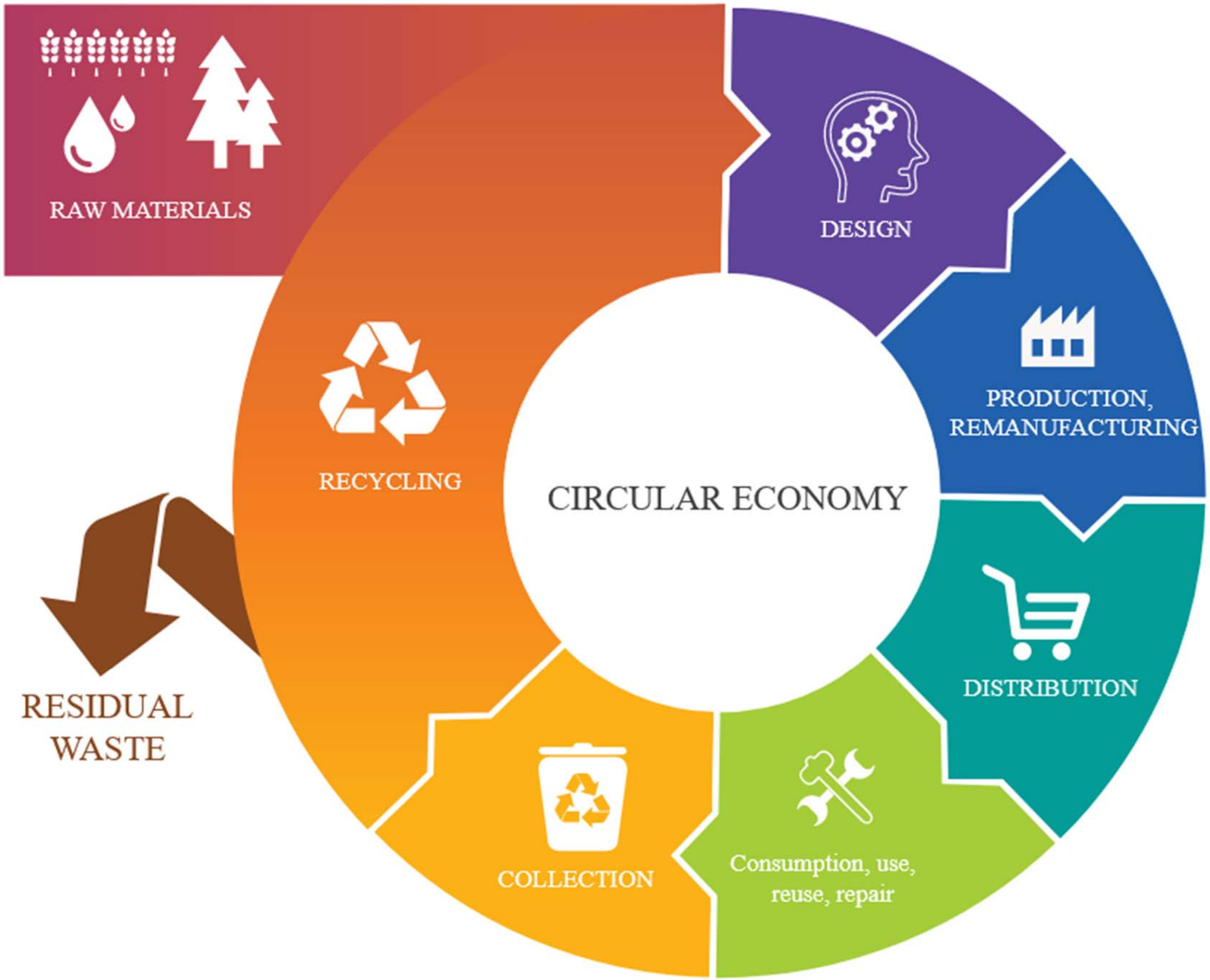
EIT HEI Initiative

# COPPER BIOMETALLURGY: EXTRACTIVE PROCESSES USING BACTERIA



Francisco Córdoba García
Department of Integrated Sciencie
University of Huelva (SW Spain)




[European Parliament](www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits).
www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits

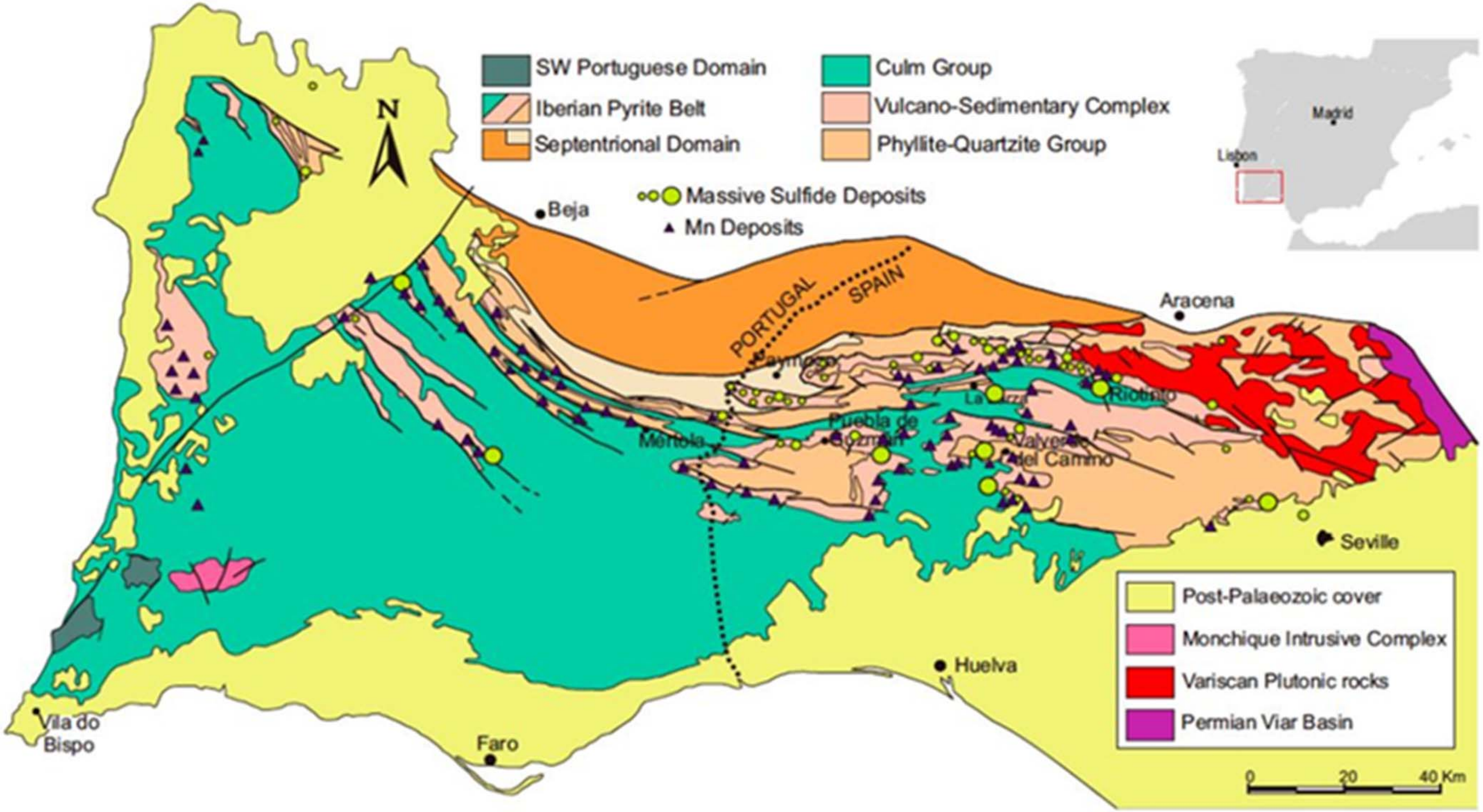

LEARN FROM NATURE:
Knowledge and research are necessary!

# OBJECTIVES OF THE MODULE

(1) Understand the metabolism of iron and/or sulfur oxidizing acidophilic bacteria.
(2) Explain the implication of bacteria in the generation of Acid Mine Drainage.
(3) Know and understand the experimental methodology prior to the use of acidophilic bacteria in the mining and metallurgical industries.
(4) Recognize the possible applications of such bacteria in copper metallurgy.
(5) Review the state of the art for the use of acidophilic bacteria in the mining industry: experiences in Chile, China and other countries.
(6) Know examples of recovery of metals from industrial waste through biotechnological techniques

# THE IBERIAN PYRITIC BELT

Probably the largest massive sulfide deposit in the world.



# MINES AND ACID RIVERS IN THE IPB






# ACID MINE DRAINAGE (AMD)

$$4FeS_2 + 15O_2 + 14\,H_2O \rightarrow 4Fe(OH)_3 + 8SO_4^{2-} + 16H^+$$

pH < 4

**$Fe_3^{\,+}$**

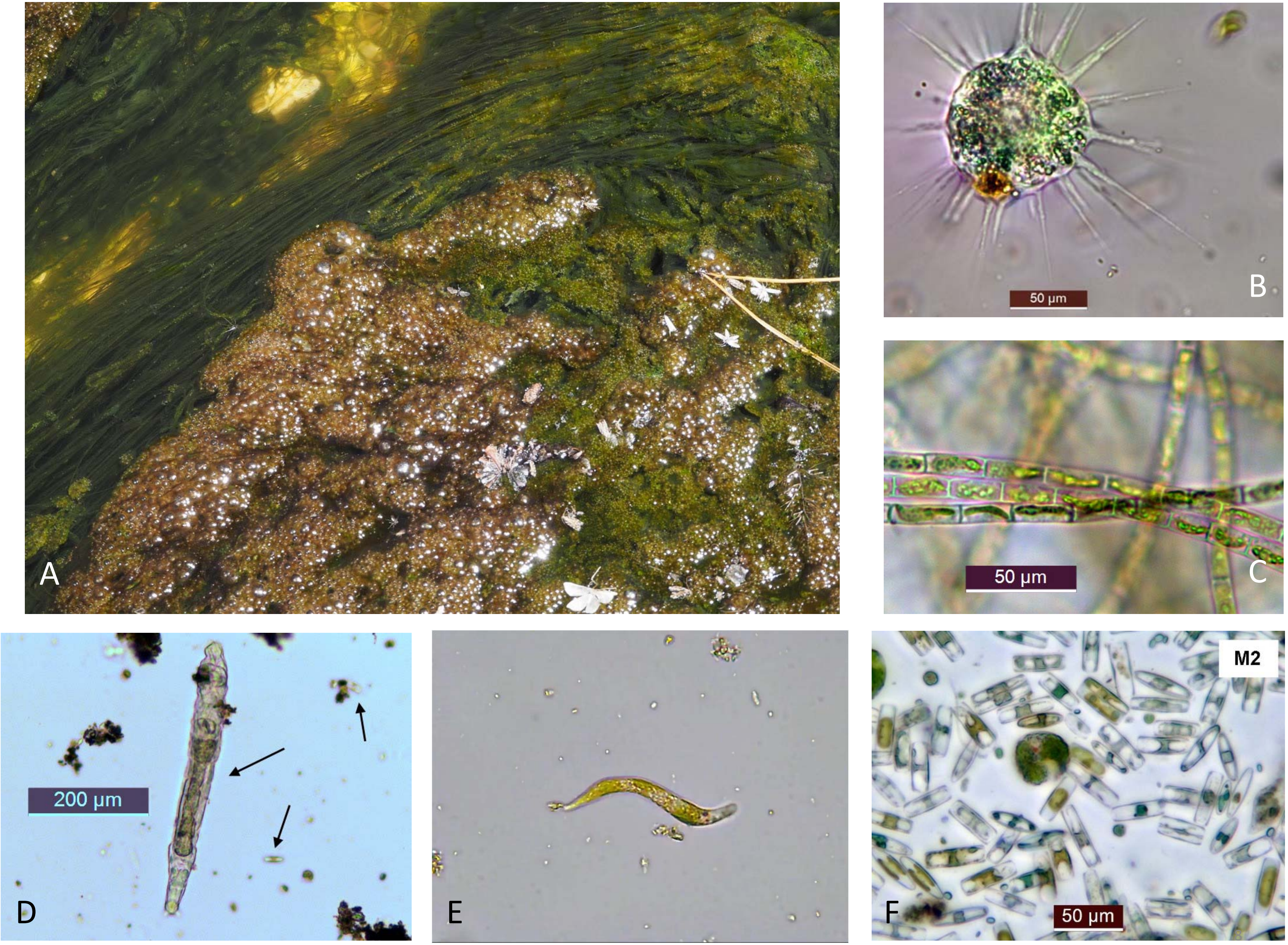
$$4FeS_2 + 15O_2 + H_2O \rightarrow 4Fe^{3+} + 8SO_4^{2-} + 4H^+$$ *Bacteria*

$$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+$$

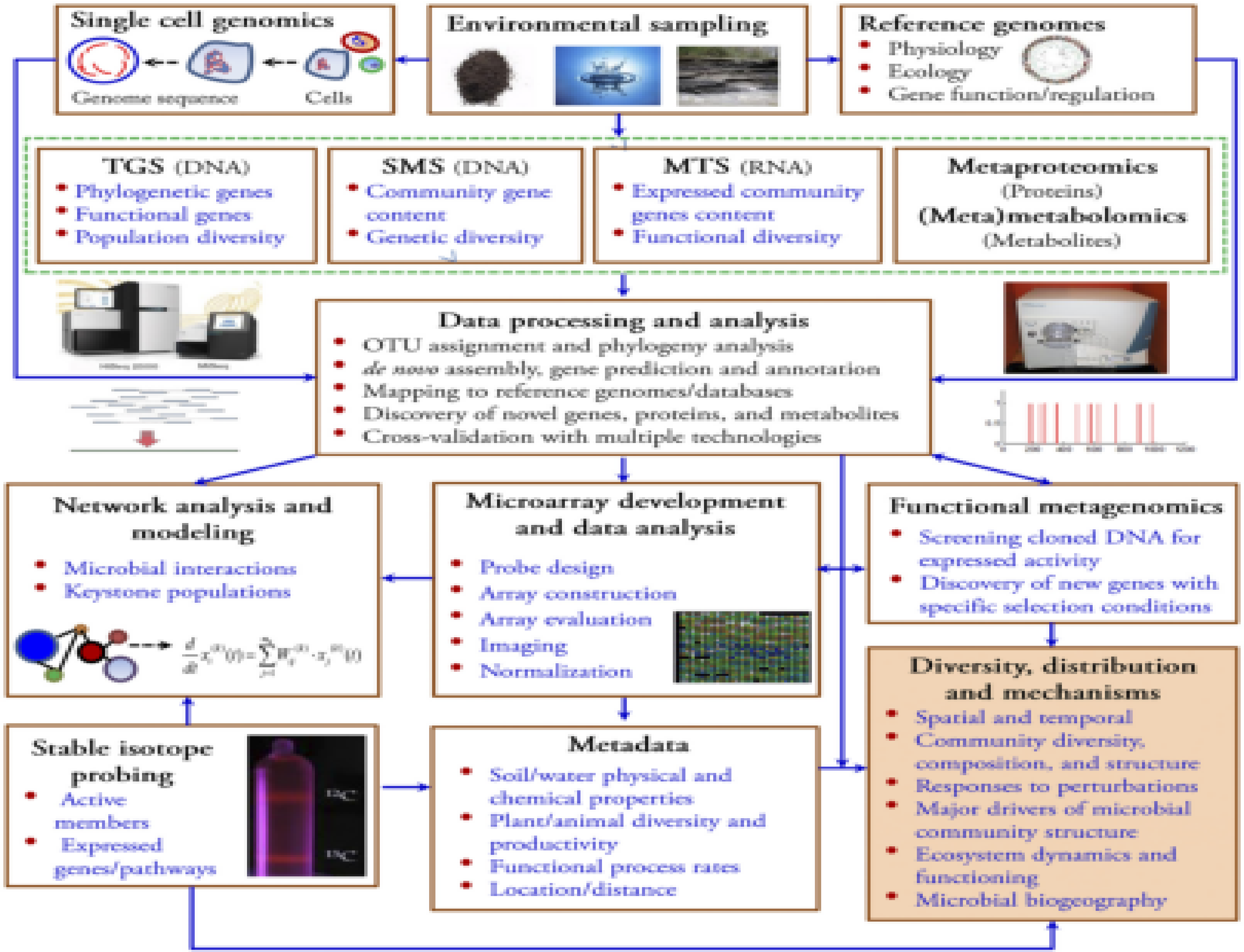



Sánchez-España et al., 2007; Johnson et al., 2012

# MICROORGANIMS OF AMD RIVERS



# METAGENOMIC ANALYLIS



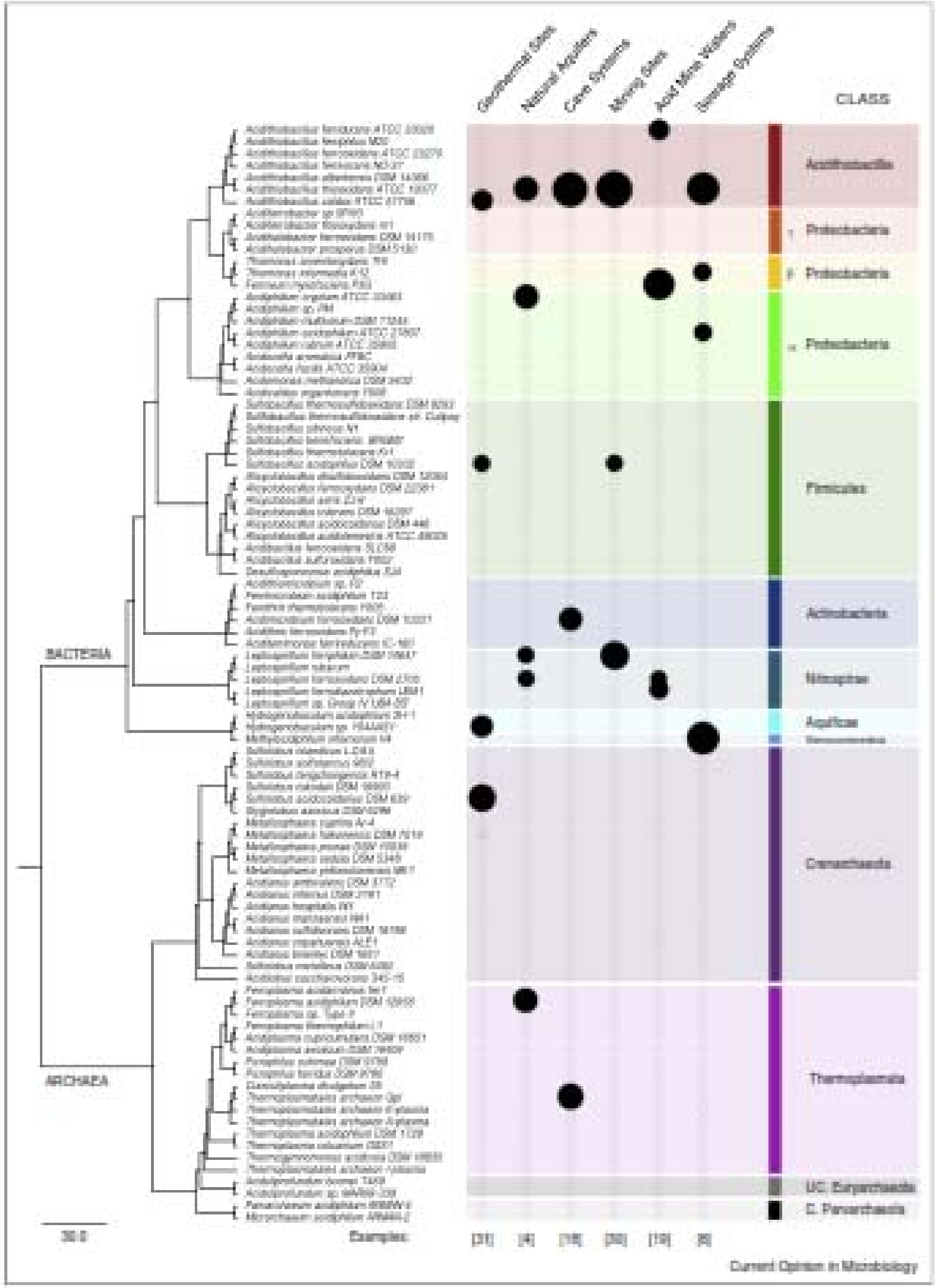



Zhou et al., 2015; https://mbio.asm.org/content/6/1/e02288-14/F1

# THE DIVERSITY OF BACTERIA IS EXTRAORDINARY

| Iron-oxidizing acidophiles | Iron-reducing acidophiles | Iron-oxidizing/reducing acidophiles |
|---|---|---|
| **BACTERIA** | | |
| *Leptospirillum (L.)*[1] | *Acidiphilium (A.)*[2/3] | *Acidithiobacillus (At.)*[1] |
| *L. ferrooxidans* | *A. cryptum*[2] | *At. ferrooxidans* |
| *L. ferriphilum* | *A. acidophilum*[3] | *At. ferrivorans* |
| *"L. ferrodiazotrophum"* | *A. angustum/rubrum*[2] | *Acidiferrobacter thiooxydans*[1] |
| *"Ferrovum myxofaciens"*[1] | *A. organovorum*[2] | *Ferrimicrobium acidiphilum*[2] |
| *"Thiobacillus prosperous"*[1] | *A. multivorum*[2] | *Acidimicrobium ferrooxidans*[3] |
| | *Acidocella (Ac.)*[2] | *Ferrithrix thermotolerans*[2] |
| | *Ac. facilis* | *Sulfobacillus (Sb.)*[3] |
| | *"Ac aromatica"* | *Sb. acidophilus* |
| | *Acidobacterium*[2] | *Sb. thermosulfidooxidans* |
| | *Acb. capsulatum* | *Sb. benefaciens* |
| | *Acidobacterium* spp. | *Alicyclobacillus (Alb.)* |
| | | *Alb. tolerans* |
| | | *Alb. ferrooxydans* |
| | | *Alb. aeris* |
| | | *Alb. pohliae* |
| | | *Alicyclobacillus* sp. GSM |
| **ARCHAEA** | | |
| *Sulfolobus (S.)* | | *Ferroplasma (Fp.)* spp. |
| *S. metallicus* | | *Fp. acidiphilum* |
| *S. tokodaii* | | *"Fp. acidarmanus"* |
| *Metallosphaera sedula* | | *Acidiplasma (Ap.)* |
| | | *Ap. cupricumulans* |
| | | *Ap. aeolicum* |

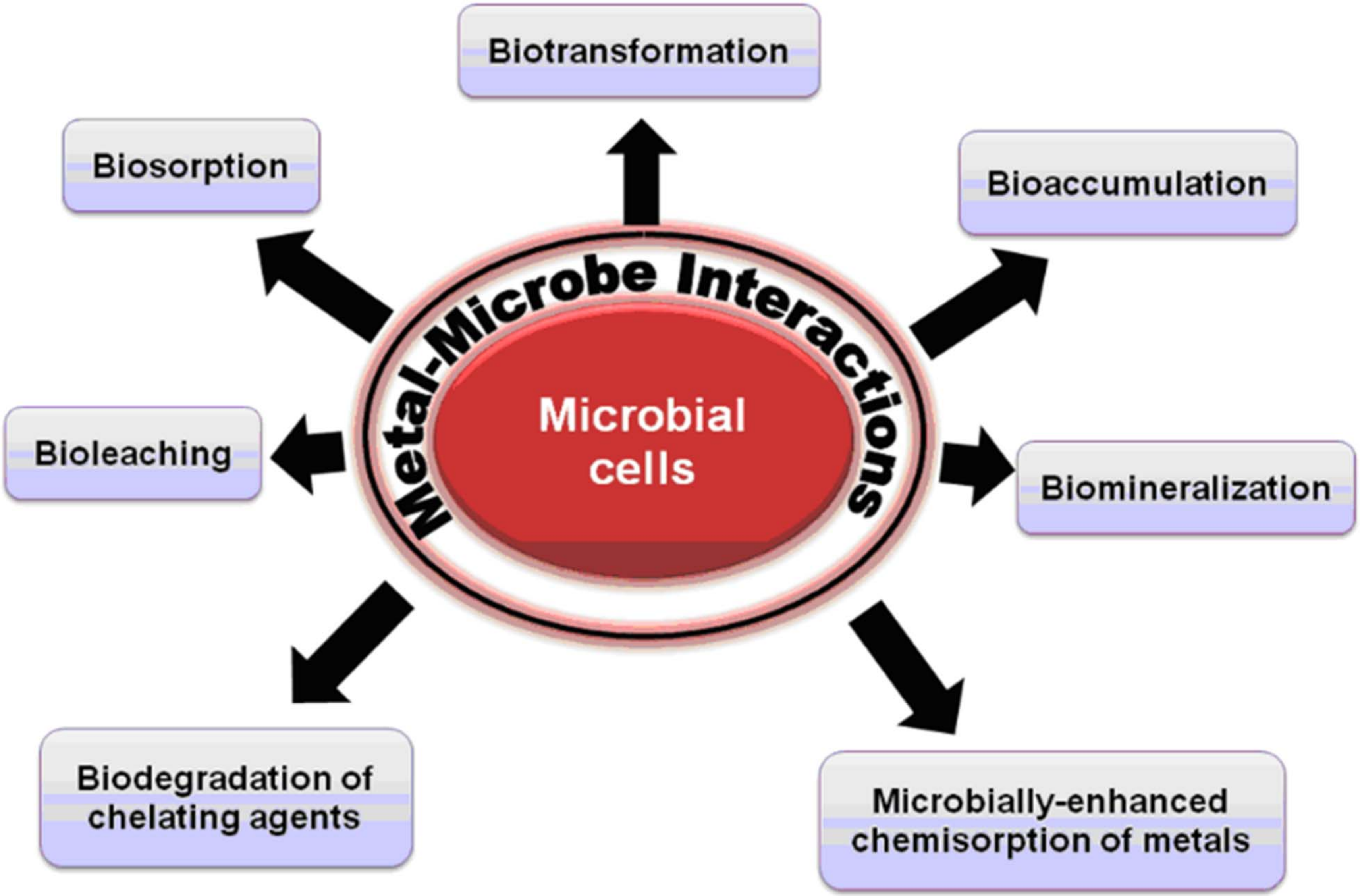
[1]Obligate autotrophs; [2]obligate heterotrophs; [3]facultative autotrophs.






Johnson et al., 2012; Quatrini y Johnson, 2018

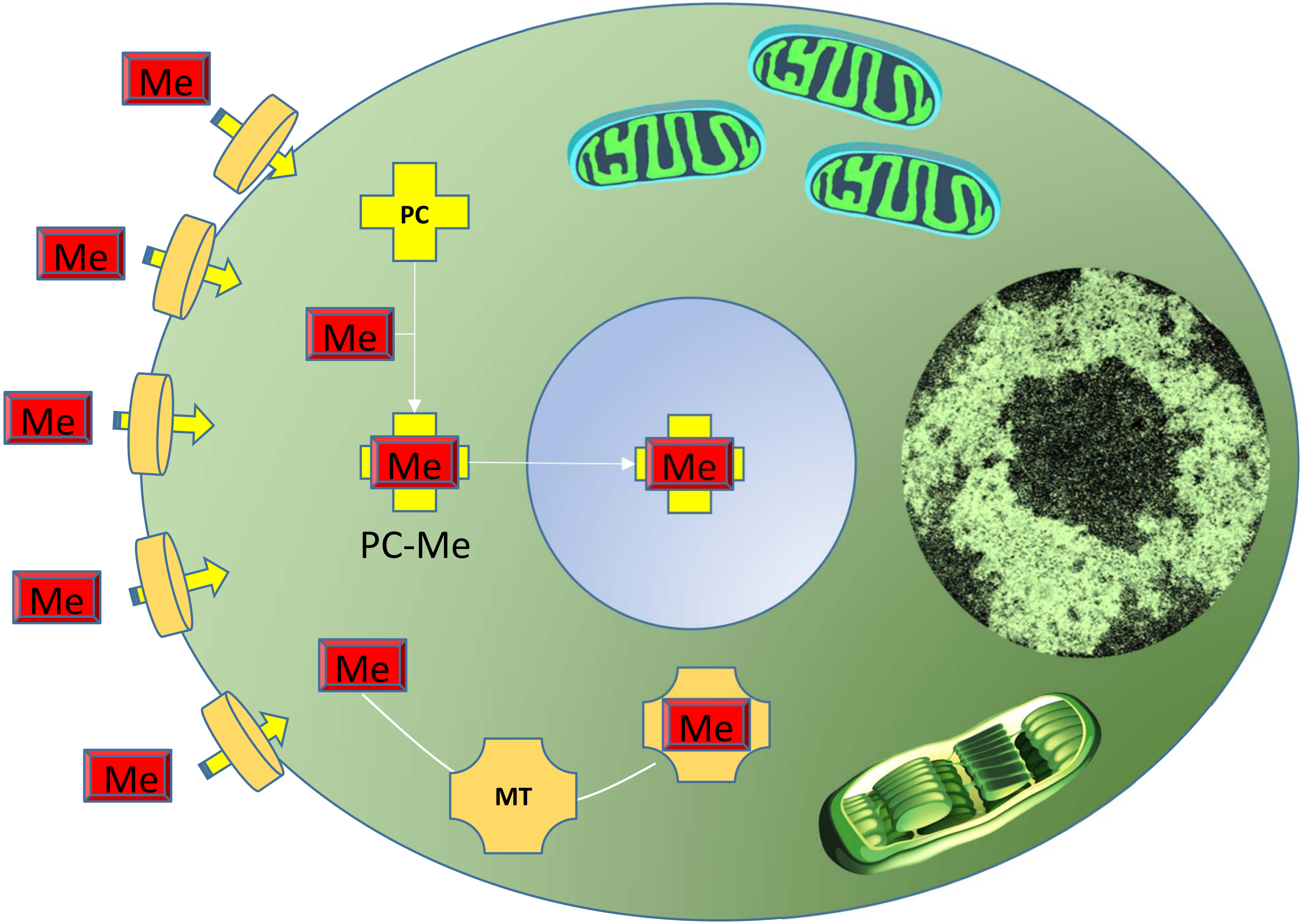
# METAL-BACTERIA INTERACTIONS





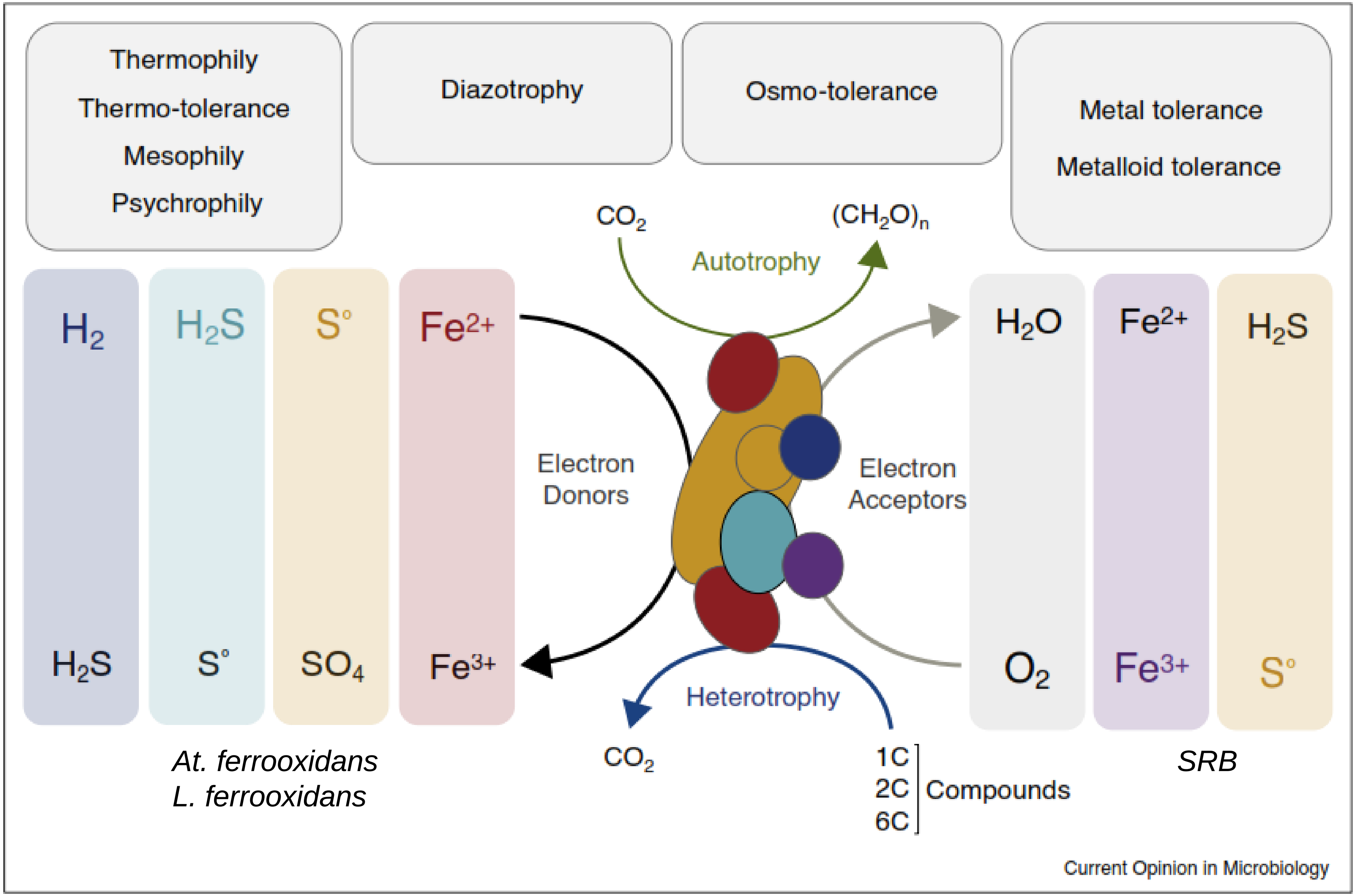

Tabak et al., 2005; Ahemad, 2012

# METAL-ALGAE INTERACTIONS




(based on Aguilera et al, 2020)

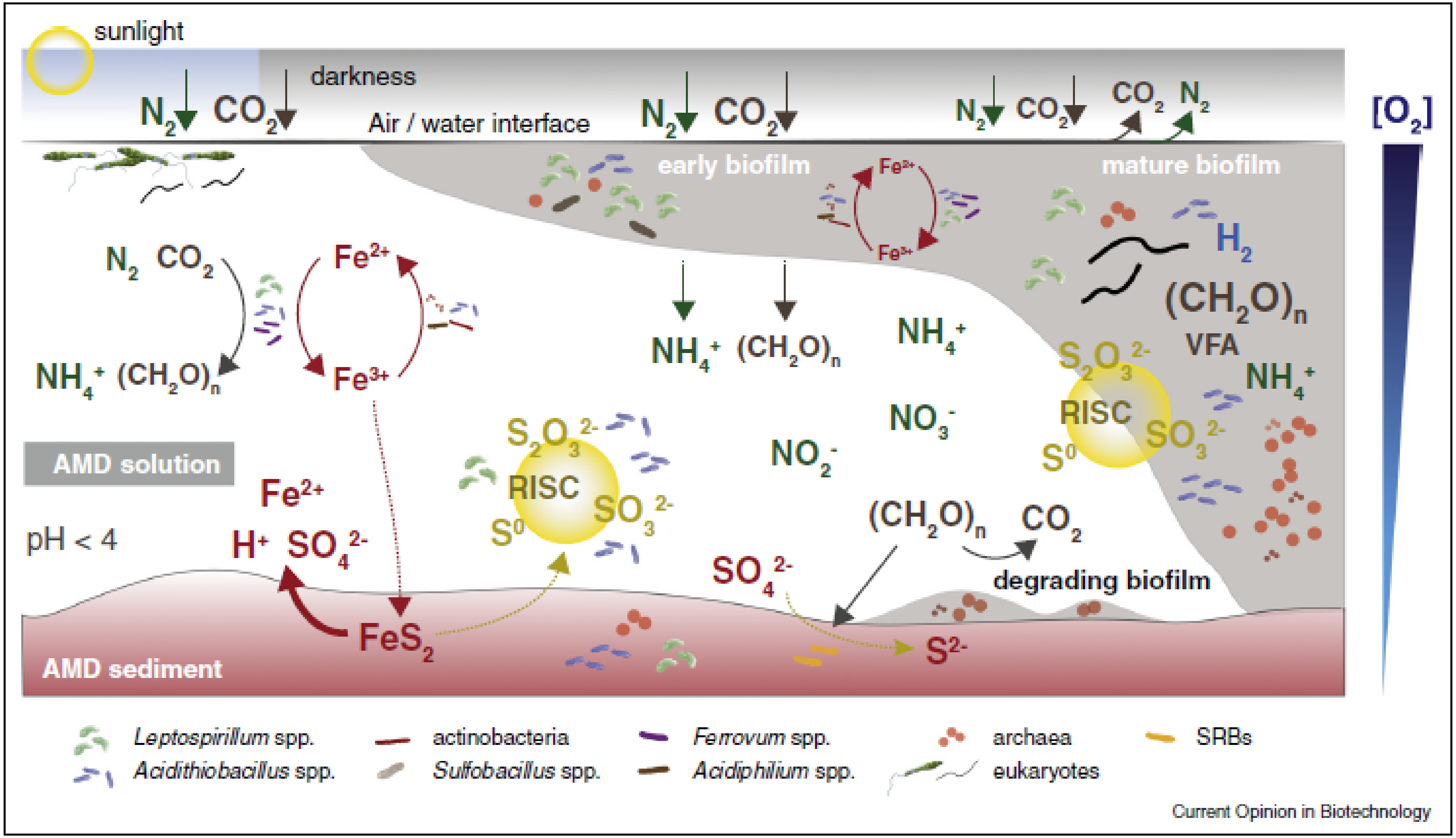
# CHEMOLITOTROPHIC AND HETEROTROPHIC BACTERIA






Quatrini R y Johnson DB (2018). Ver también: González-Toril et al., 2003

# BACTERIAL ENVIRONMENTS IN AMD-POLLUTED WATERS

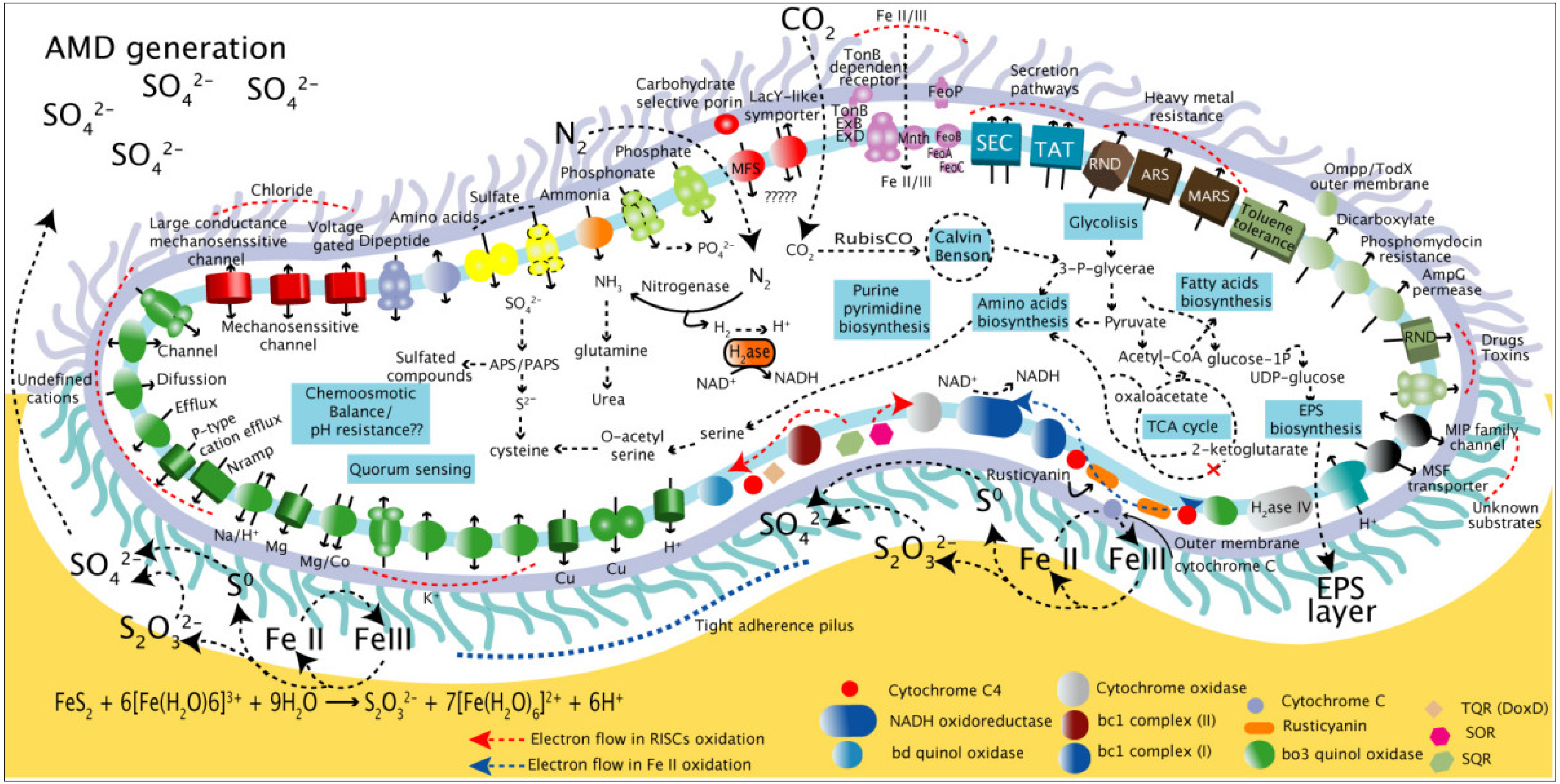


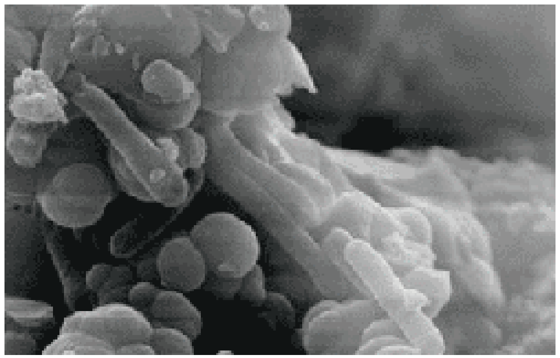

3 environments are considered: air/water interface, biofilms and sediments. Auto- and diazotrophic bacteria fix CO2 and N2 through reduction coupled with oxidation of Fe(II). Redox reactions carried out by lithotrophic bacteria that consume metal sulfides (RISC) are carried out through the formation of biofilms and collaborative metabolic processes. In sediments, a variety of heterotrophic bacteria degrade biofilms under microaerobic and anaerobic conditions, while sulfate-reducing bacteria regenerate RISCs.



Méndez-García et al., 2014; Chen et al., 2016

# *ACIDITHIOBACILLUS FERROXIDANS*



*Acidithiobacillus ferrooxidans* is considered the main responsible for Acid Mine Drainage



Valdés et al., 2008; Osorio et al., 2013

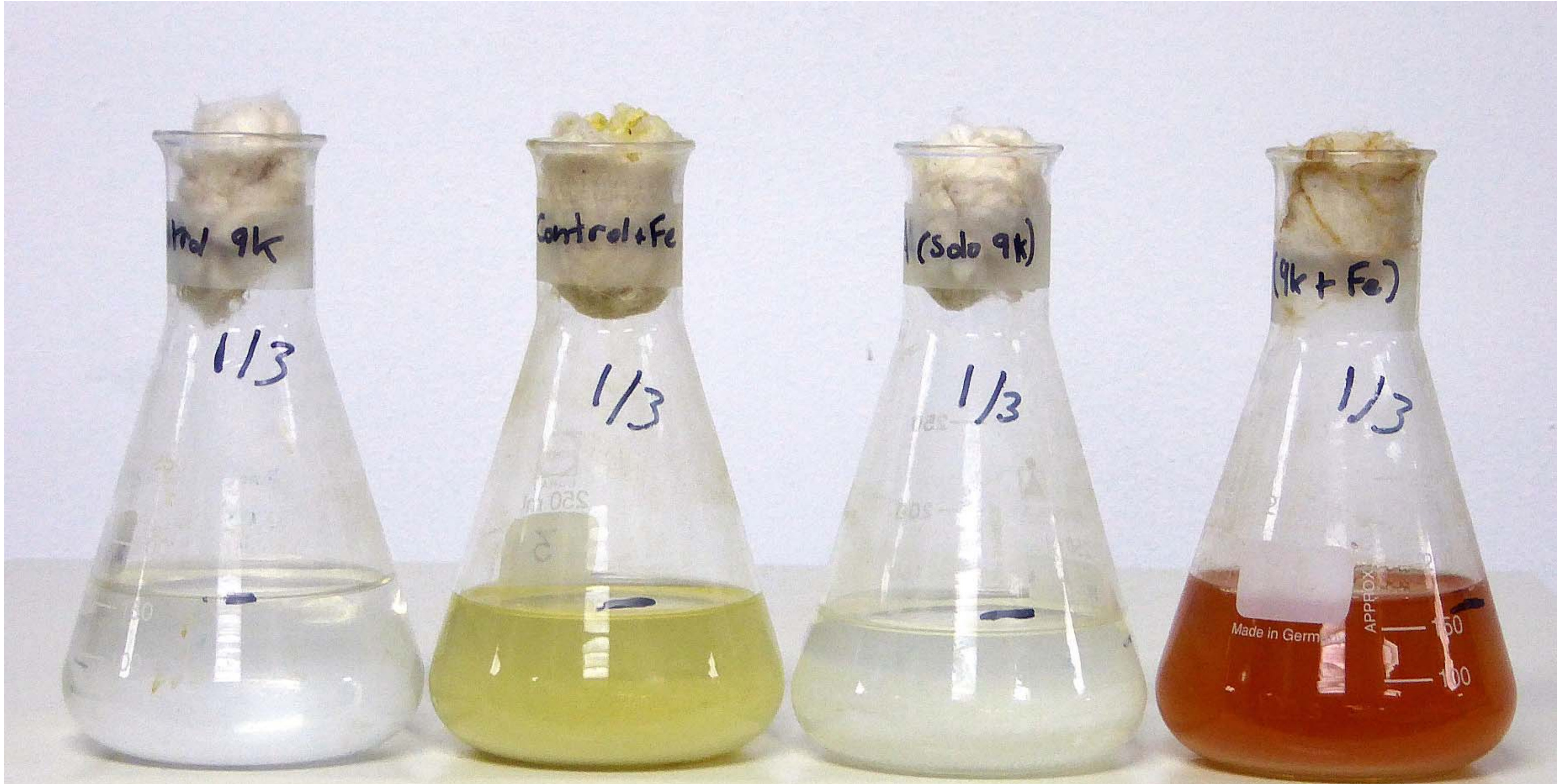
# SAMPLING OF BACTERIA IN AMD-POLLUTED RIVERS

Testing physical-chemical properties

Collecting bacterial samples

| | Non polluted river | AMD-polluted river |
|---|---|---|
| pH | 6.9 | 2.3 |
| EC (mS/cm) | 0.3 | 3.3 |
| Eh (mV) | 472 | 890 |

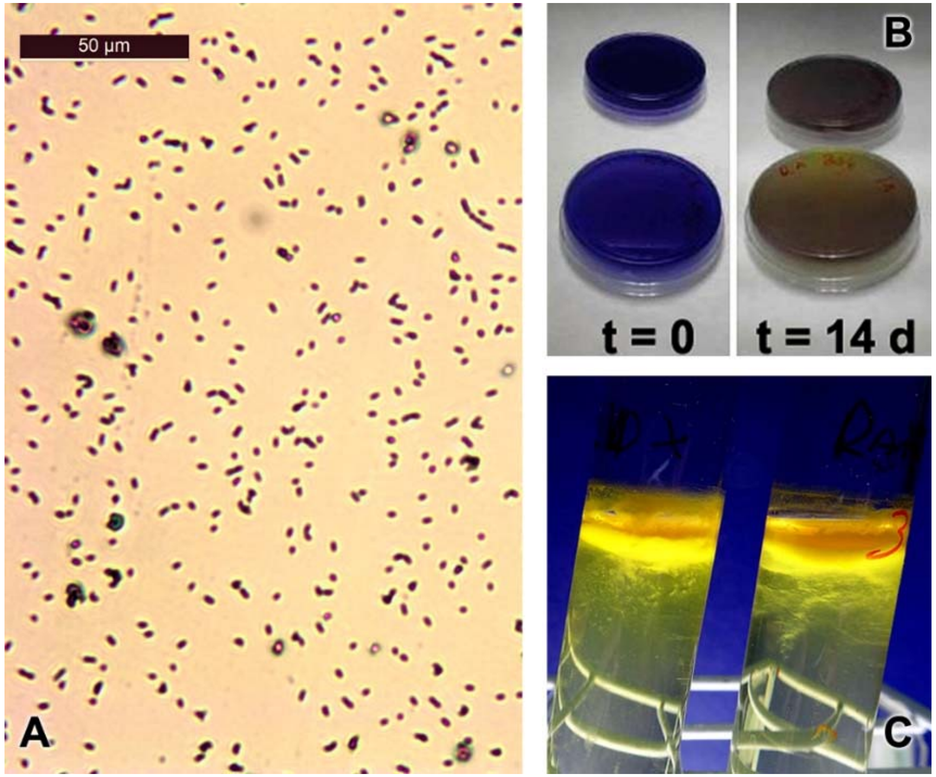
# 1. GROWING BACTERIA AND REPRODUCING AMD

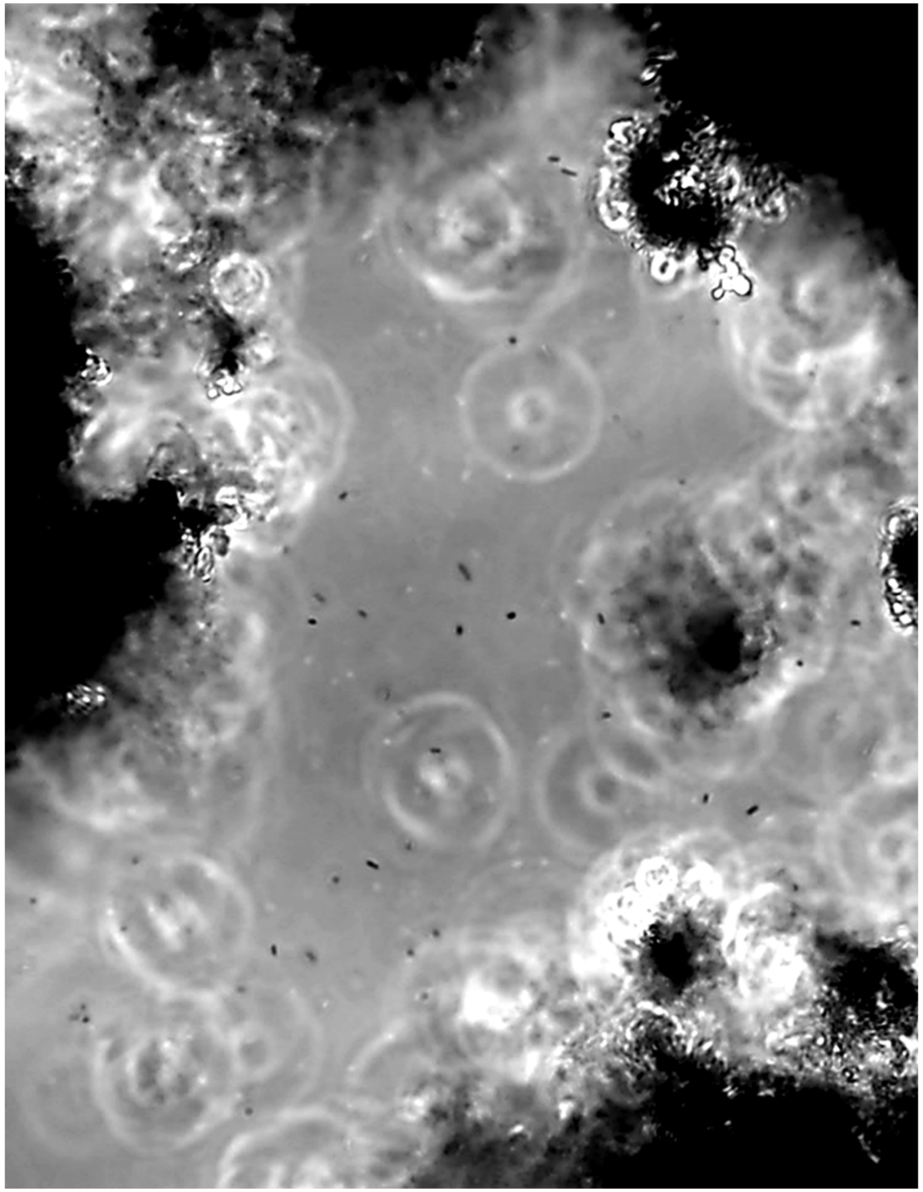


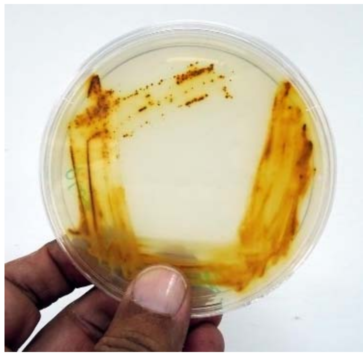

| Only 9K | 9K + $Fe^{2+}$ | 9K + bacteria | 9K + $Fe^{2+}$ + bacteria |
|---|---|---|---|

Inoculum: consortium of bacteria from AMD-polluted river. Specific growth medium: 9K. Source of iron: $FeSO_4$

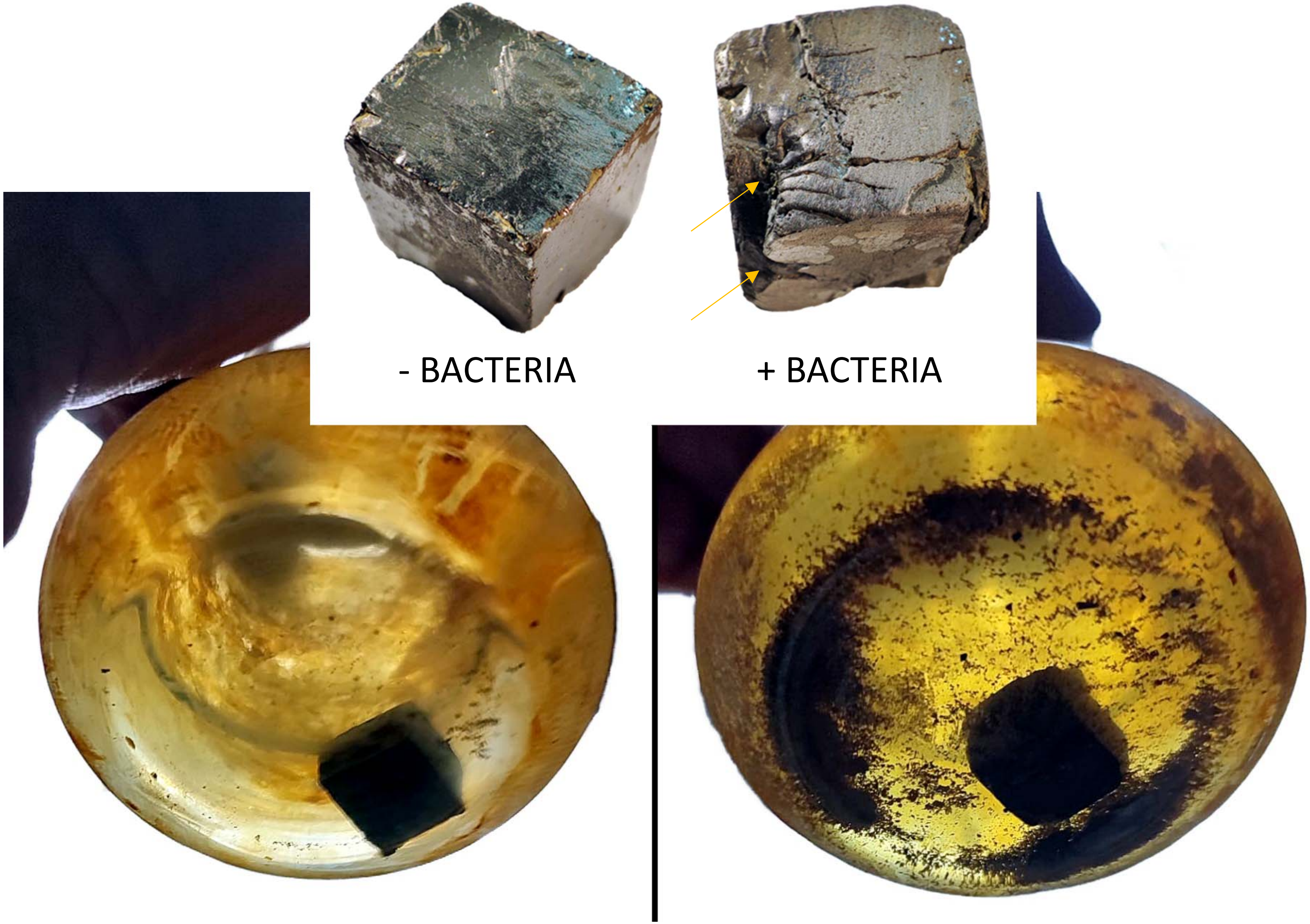
# 2. TESTING THE PRESENCE OF BACTERIA





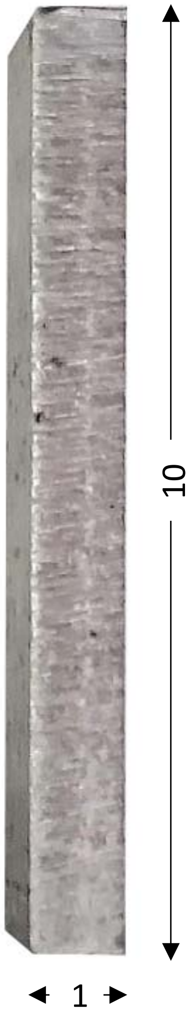
# 3. TESTING BIOLEACHING OF PYRITE




STERILE MEDIUM (WITHOUT BACTERIA)

MEDIUM WITH BACTERIA

# 4. TESTING BIOCORROSION OF CARBON STEEL

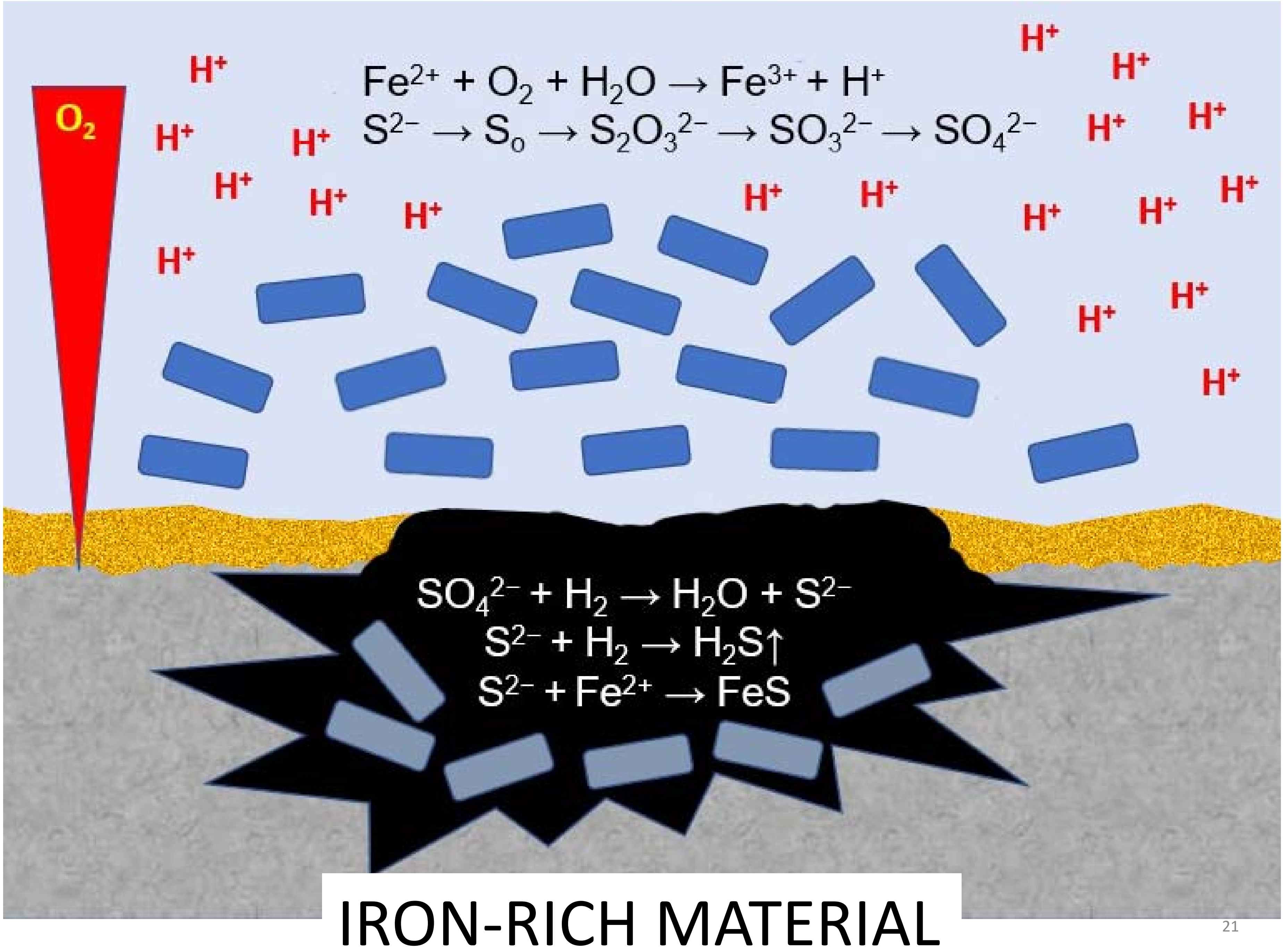



Carbon steel
test tube
(10x1 cm)

Medium + bacteria - S

Medium + bacteria + S

# SUGGESTED CONCLUSSIONS



# *BIOMACHINING* OF COPPER SLAGS

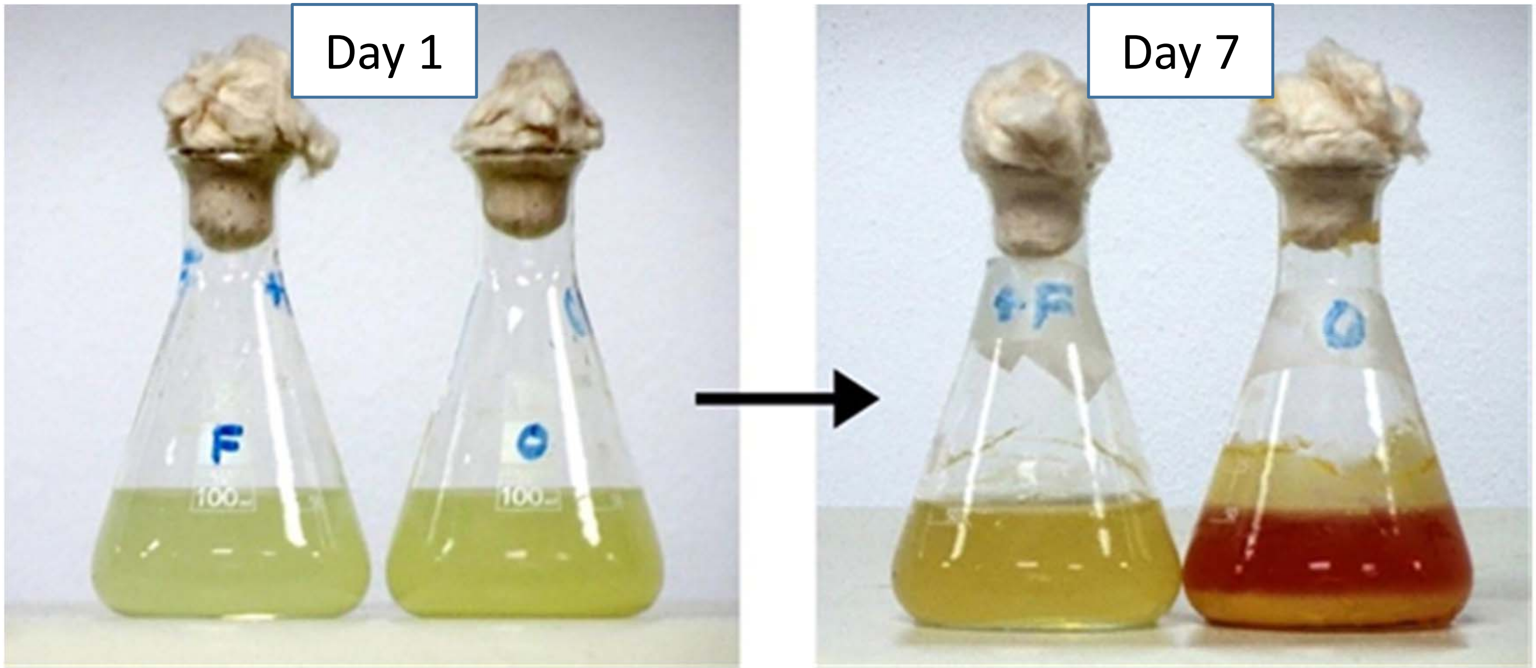
| Components (%) ± SD | |
|---|---|
| Cu | 1,30 ± 0.190 |
| Fe | 44,93 ± 0.870 |
| $Fe_3O_4$ | 13,63 ± 1.790 |
| $SiO_2$ | 29,58 ± 0.81 |
| Al | 1,68 ± 0.150 |
| Ca | 0,94 ± 0.130 |
| K | 0,48 ± 0.043 |
| Mg | 0,40 ± 0.053 |
| Na | 0,07 ± 0.026 |

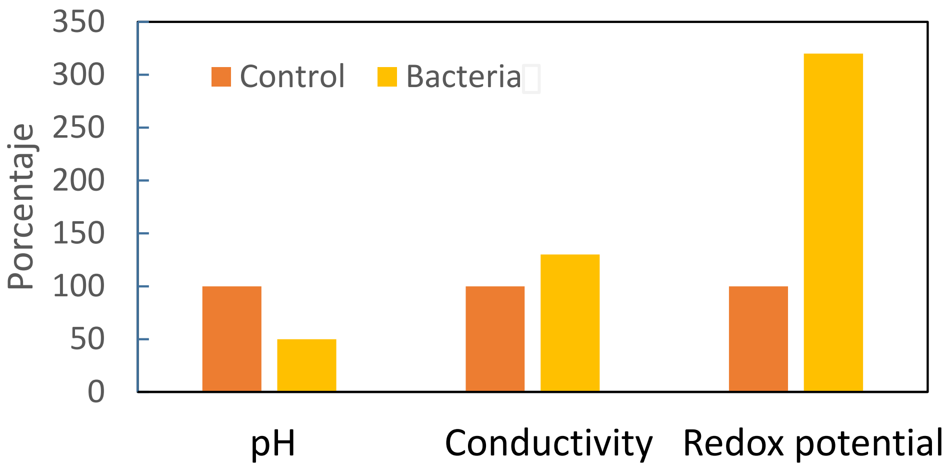

*Biomachining*: microbiologically controlled corrosion, is a process based on the elimination of a metallic material by solubilization following chemical reactions in the solution.

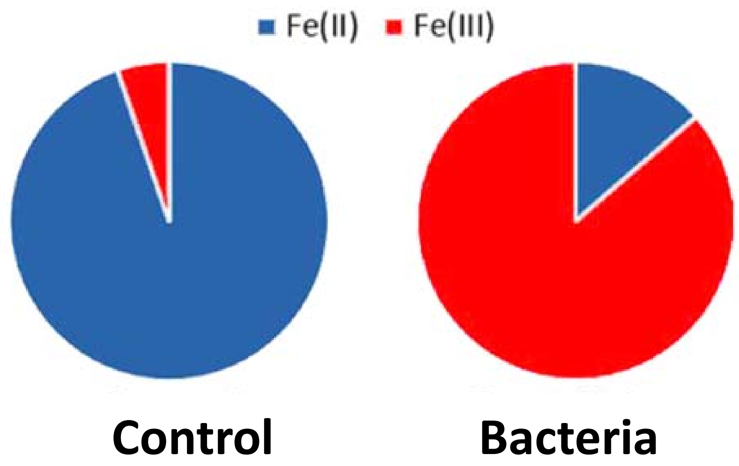


Xenofontos et al., 2015; Díaz-Tena et al., 2016

# COPPER SLAGS AS SOURCE OF IRON FOR BACTERIA

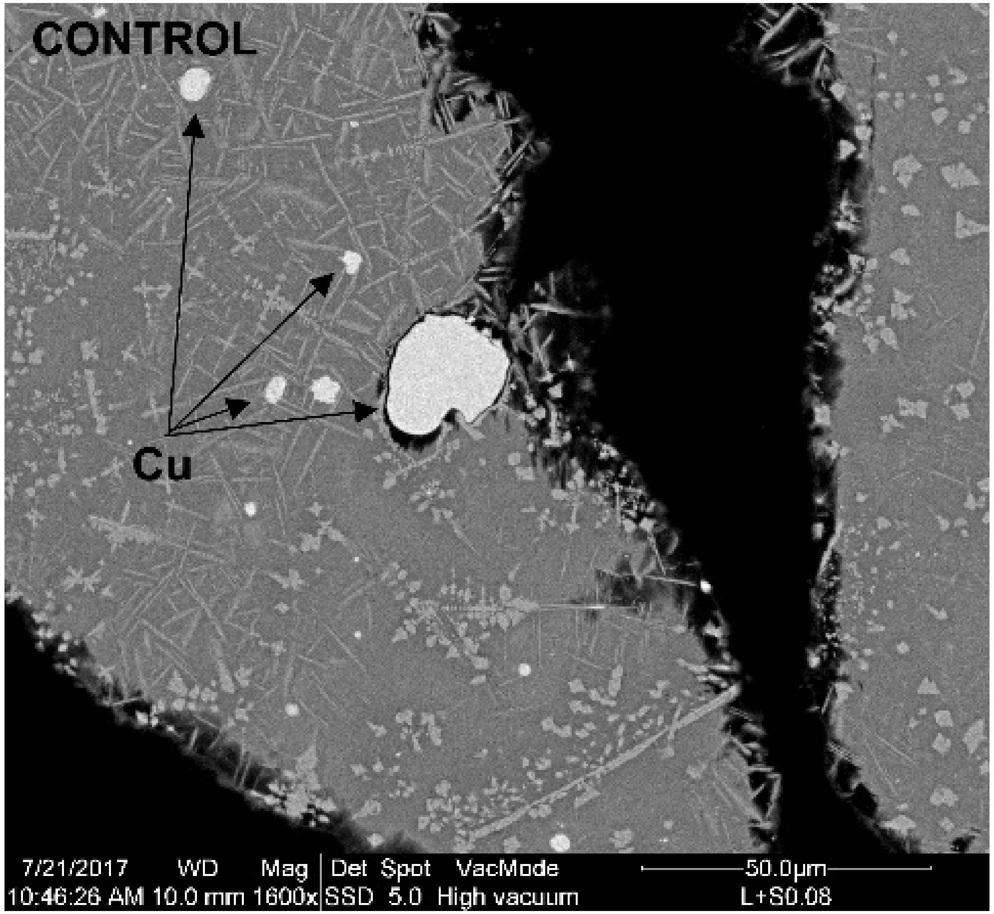


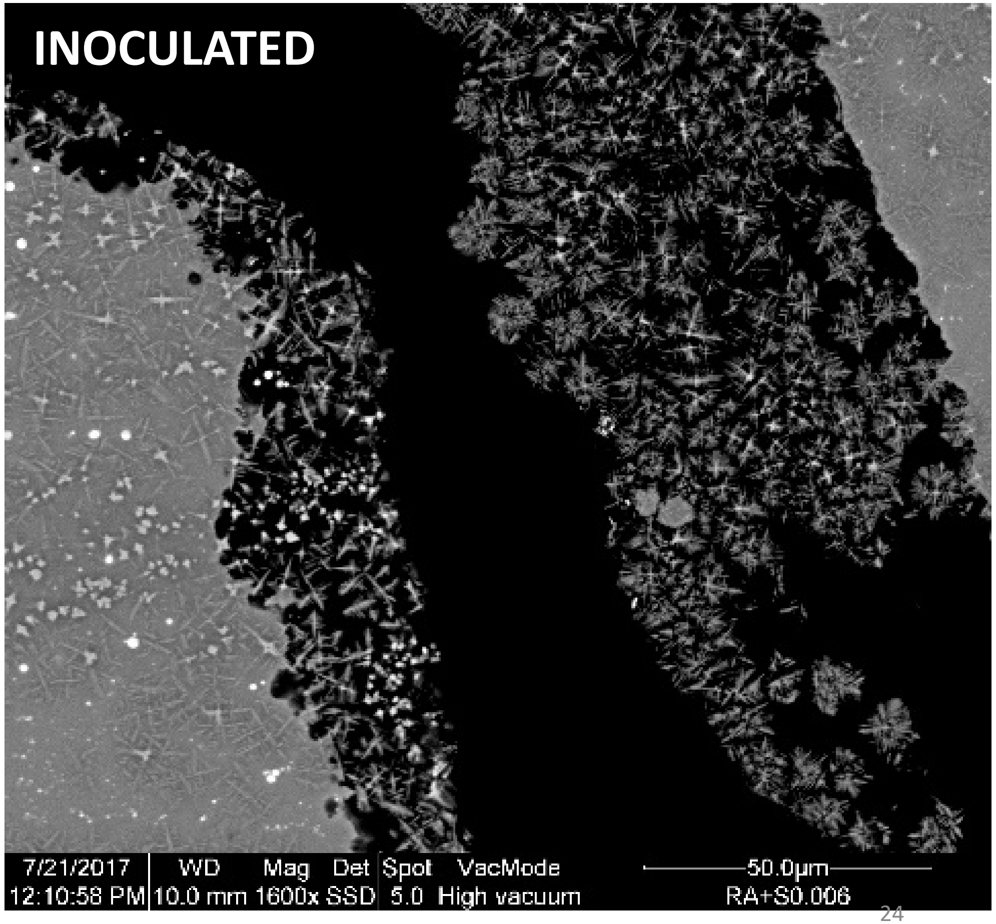



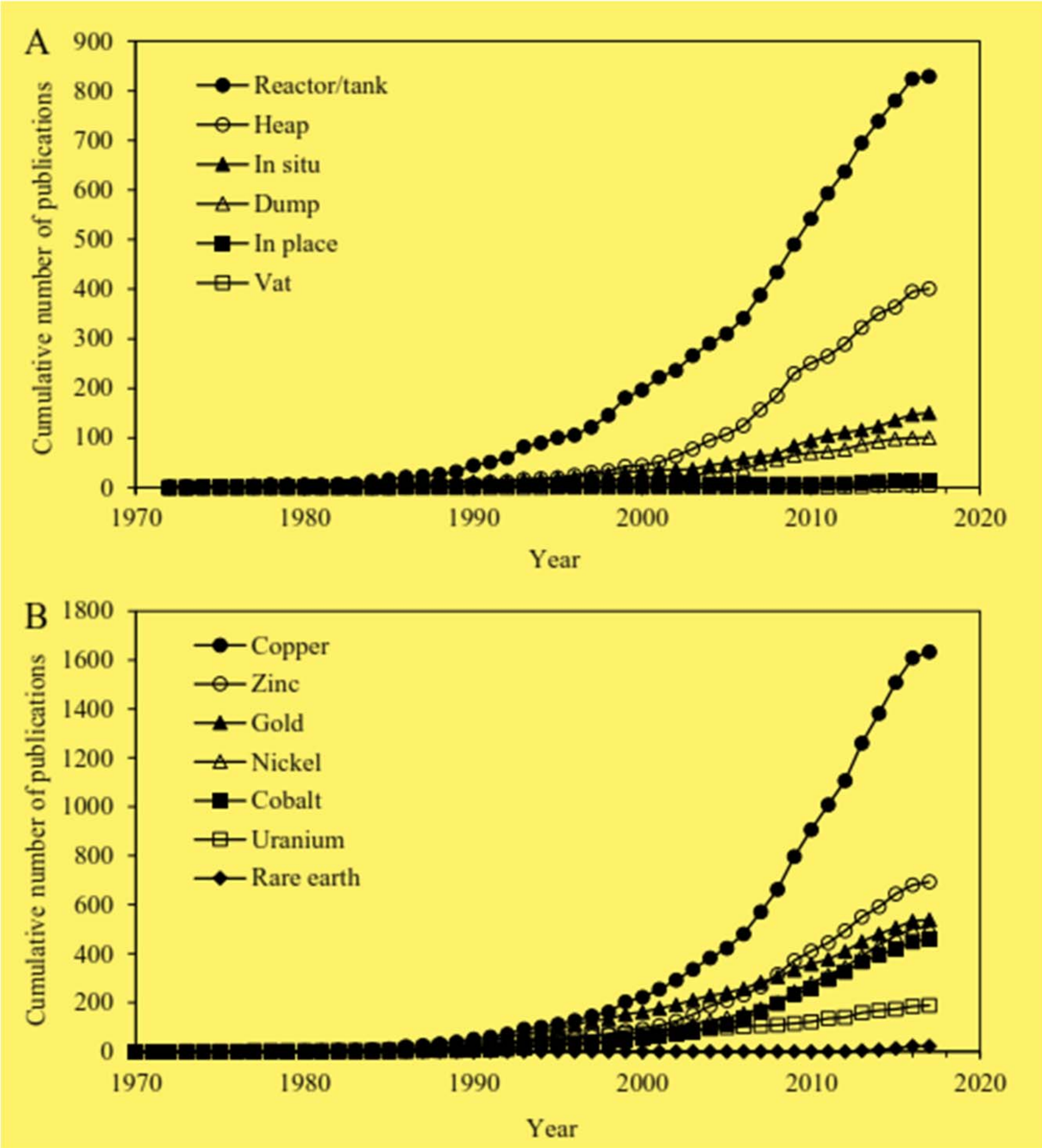
# RESULTS: 14 DAYS OF INCUBATION

| PARAMETERS | CONTROL | WITH BACTERIA | Δ (%) |
|---|---|---|---|
| Cu | 2.8 | 43.3 | 1446 |
| Fe | 168.0 | 735.5 | 338 |
| pH | 4.02 | 2.09 | -48 |
| Conductivity | 8.24 | 11.17 | 36 |
| Redox Potential | 207 | 633 | 206 |



# *BIOLEACHING, BIOOXIDATION, BIOMINING, BIOMETALLURGY*
# NUMBER OF SCIENTIFIC PAPERS/YEAR (SCOPUS)



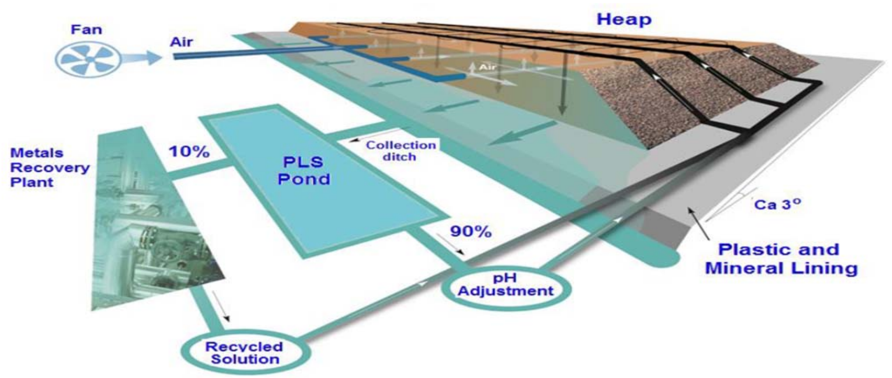

About 180000 papers from 1990.



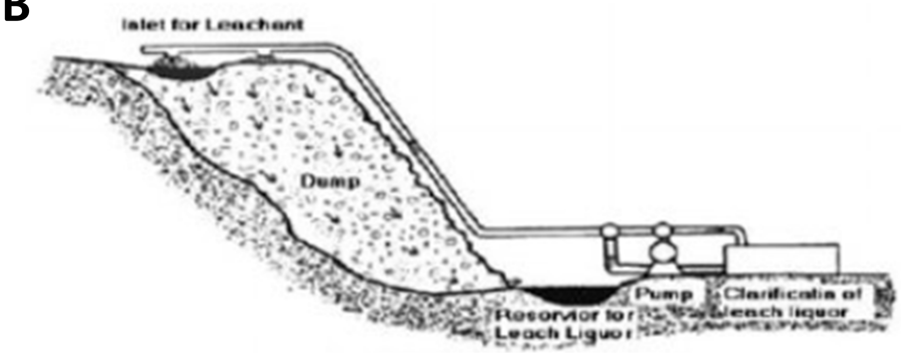
Kaksonen et al., 2017; Kucuker & Kutcha, 2018

# BIOMINING: COMMON STRATEGIES

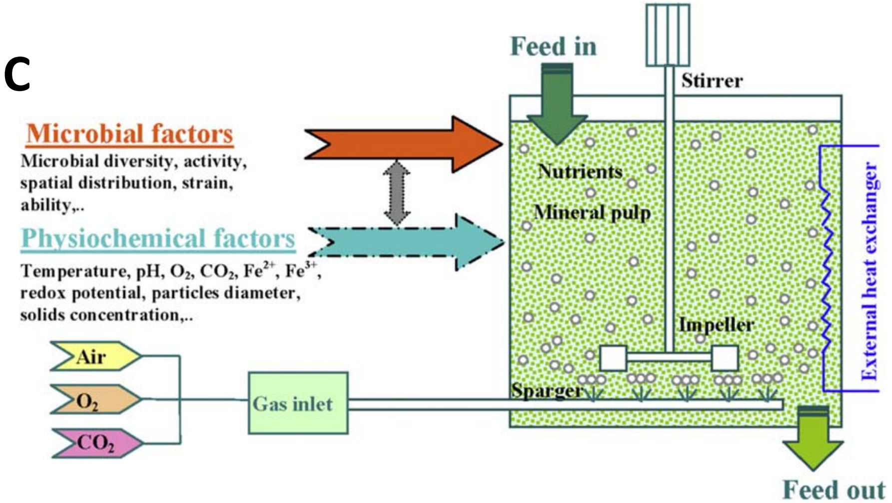
A




B




C




(BASED ON HTTP://WWW.SPACESHIP-EARTH.ORG/REM/NAEVEKE.HTM Y MAHMOUD ET AL., 2017)

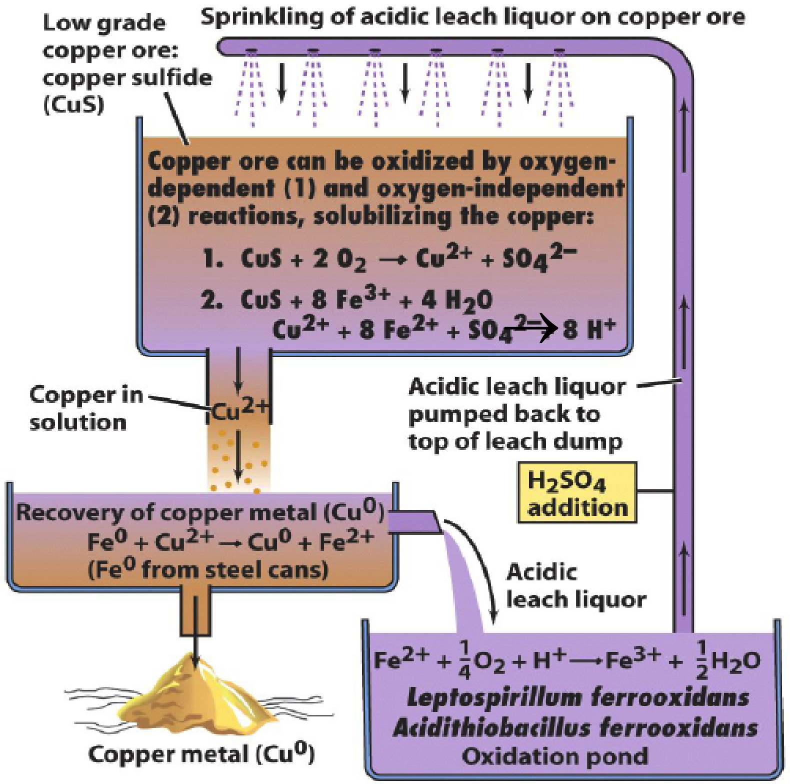
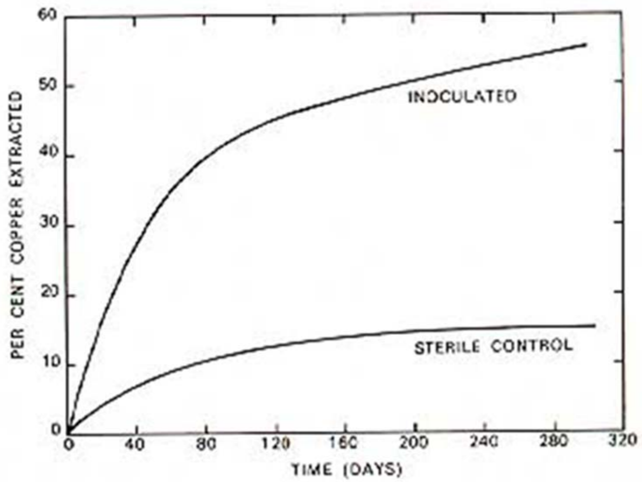



Figure 19-38 Brock Biology of Microorganisms 11/e

# LARGEST COPPER PRODUCING COUNTRIES (2020)

**1. Chile – 5.7 million tonnes**

**2. Peru – 2.2 million tonnes**

**3. China – 1.7 million tonnes**

**4. Democratic Republic of Congo – 1.3 million tonnes**

**5. United States – 1.2 million tonnes**

The Escondida project in northern Chile is the world's largest copper mine.

# COPPER BIOLEACHING IN LARGE AND MEDIUM-SIZED MINES IN CHILE

| Mine | Operator | Production tonne/year | Ore grade % | Period of operation |
|---|---|---|---|---|
| Lo Aguirre | Sociedad Minera Pudahuel | 15,000 | 1.5 | 1980-2001 |
| Cerro Colorado | BHP Billiton | 130,000 | 1.0 | 1993-present |
| Ivan | Minera Milpo | 10,000 | 2.1 | 1994-present |
| Quebrada Blanca | Aur Resources | 82,000 | 0.9 | 1994-present |
| Chuquicamata | CODELCO | 12,500 | 0.3 | 1994-present |
| Andacollo | Aur Resources | 22,500 | 0.6 | 1996-present |
| Dos Amigos | Cemin | 10,000 | 2.5 | 1996-present |
| Los Bronces | Anglo-American | 46,400 | 0.45 | 2006-present |
| Punta del Cobre | Pucobre S.A. | | | |
| Zaldívar | Barrick | 147,000 | 1.4 | 1998-present |
| Alliance Copper | CODELCO-BHP Billiton | 20,000 | concentrate | 2004-2005 |
| Escondida | BHP Billiton | 750,000 | 0.3-0.7 | 2006-present |
| Spence | BHP Billiton | 200,000 | 1.1 | 2007-present |

| Mine | Production tonne/year | Region |
|---|---|---|
| Michilla | 42,000 | Antofagasta |
| Franke | 16,000 | Atacama |
| Tres Valles | 9,000 | Coquimbo |
| Cerro Negro | 5,000 | Valparaíso |



GENTINA Y ACEVEDO, 2013

# COMMERCIAL APPLICATIONS OF COPPER BIOLEACHING PLANTS AND GOLD BIOREACTORS

**Table 1.** Commercial copper bioheap leach plants

| Plant and Location | Size (t/day) | Years in operation |
|---|---|---|
| Lo Aguirre, Chile | 16,000 | 1980-1996 |
| Gunpowder's Mammoth Mine, Australia | In situ (1.2 Million tonne) | 1991- Present |
| Mt. Leyshon, Australia | 1,370 | 1992-1997 |
| Cerro Colorado, Chile | 16,000 | 1993-Present |
| Girilambone, Australia | 2,000 | 1993-Present |
| Ivan-Zar, Chile | 1,500 | 1994-Present |
| Quebrada Blanca, Chile | 17,300 | 1994-Present |
| Andacollo, Chile | 10,000 | 1996-Present |
| Dos Amigos, Chile | 3,000 | 1996-Present |
| Cerro Verde, Peru | 15,000 | 1996-Present |
| Zaldivar, Chile | 20,000 | 1998-Present |
| S&K Copper Project, Myanmar | 15,000 | 1998-Present |

**Table 2.** Commercial stirred-tank reactor bioleach plants for pretreatment of gold concentrate [20]

| Plant and Location | Size (tones concentrate/day) | Technology | Years in operation |
|---|---|---|---|
| Fairview, South Africa | Initially10, Expanded to 35, Expanded to 40 | BIOX | 1986-Present |
| Sao Bento, Brazil | Intially 150, Expanded | BIOX Eldorado | 1990-Present |
| Harbour Lights, Australia | 40 | BIOX | 1992-1994 |
| Wiluna, Australia | Initailly 115, expanded to 158 | BIOX | 1993-Present |
| Sansu, Ghana | Initially 720 Expanded to 960 | BIOX | 1994-Present |
| Youanmi, Australia | 120 | BacTech | 1994-1998 |
| Tamboraque, Peru | 60 | BIOX | 1990-Present |
| Beaconsfield, Australia | 70 | BacTech | 200-Present |
| Laizhou, China | 100 | BacTech | 2001-Present |



MISHRA EL AT., 2005

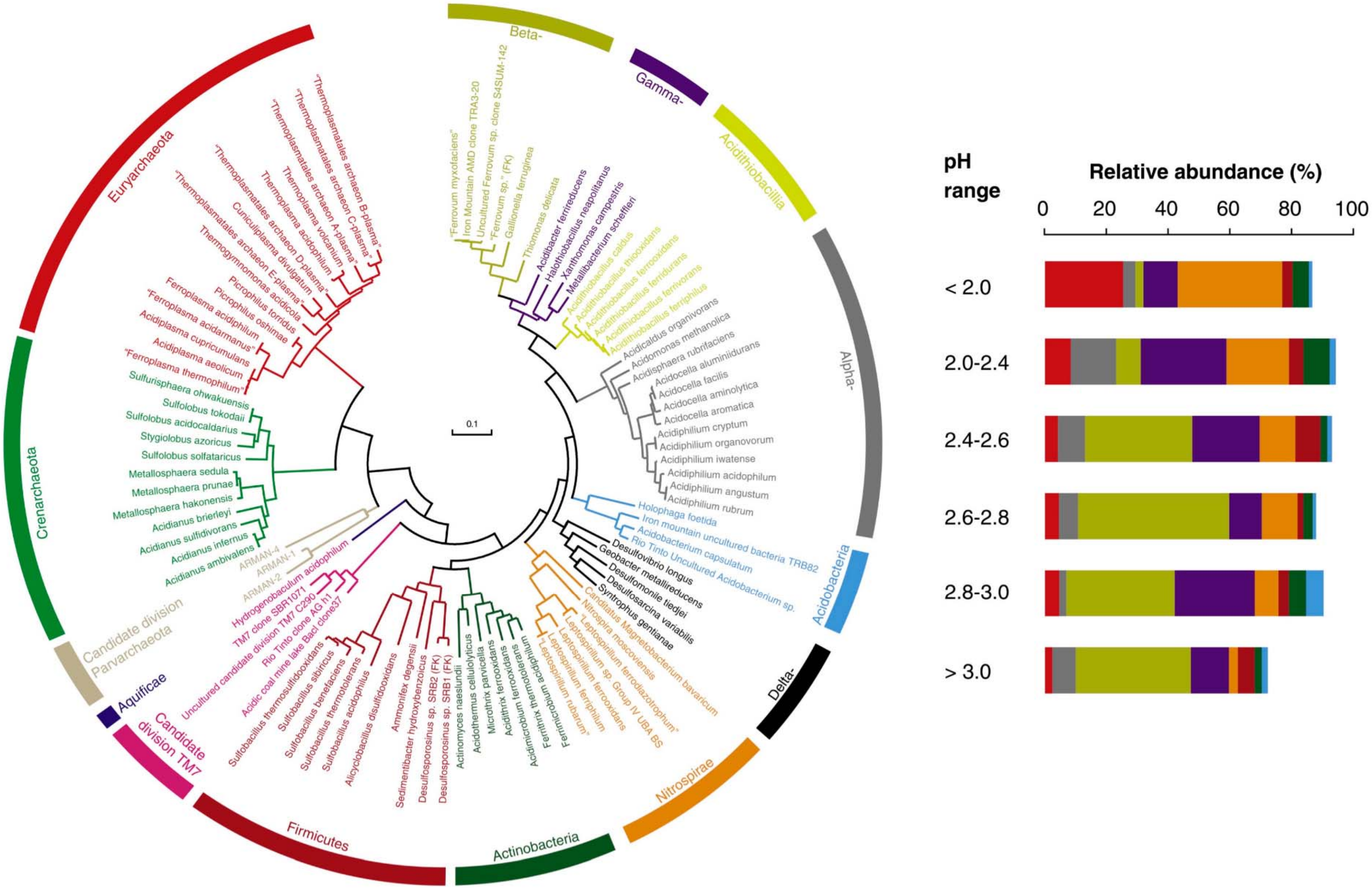
# INDUSTRIAL PLANTS OF COPPER BIOLEACHING IN CHINA


First mine: Dexing Copper Mine, 1997

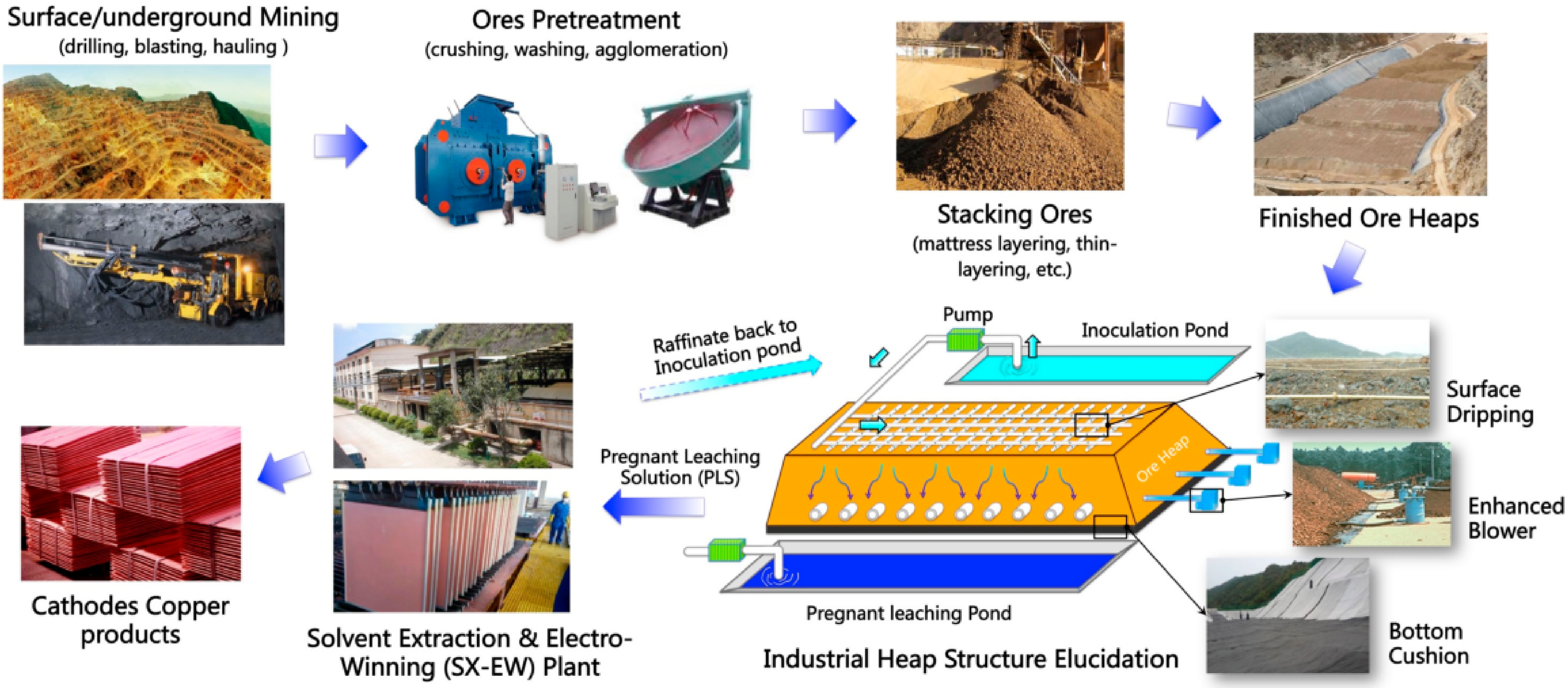


YIN ET AL., 2018

# ISOLATION, IDENTIFICATION AND ENRICHMENT OF BACTERIA



# PROCESS SCHEME OF HEAP BIOLEACHING IN INDUSTRY



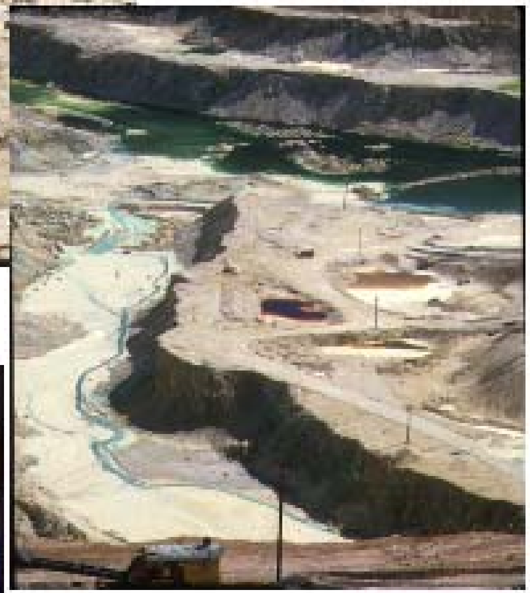



YIN ET AL., 2018

# COPPER BIOHEAPLEACHING (KENNECOTT MINE, NEW MÉXICO)

Heap

irrigation

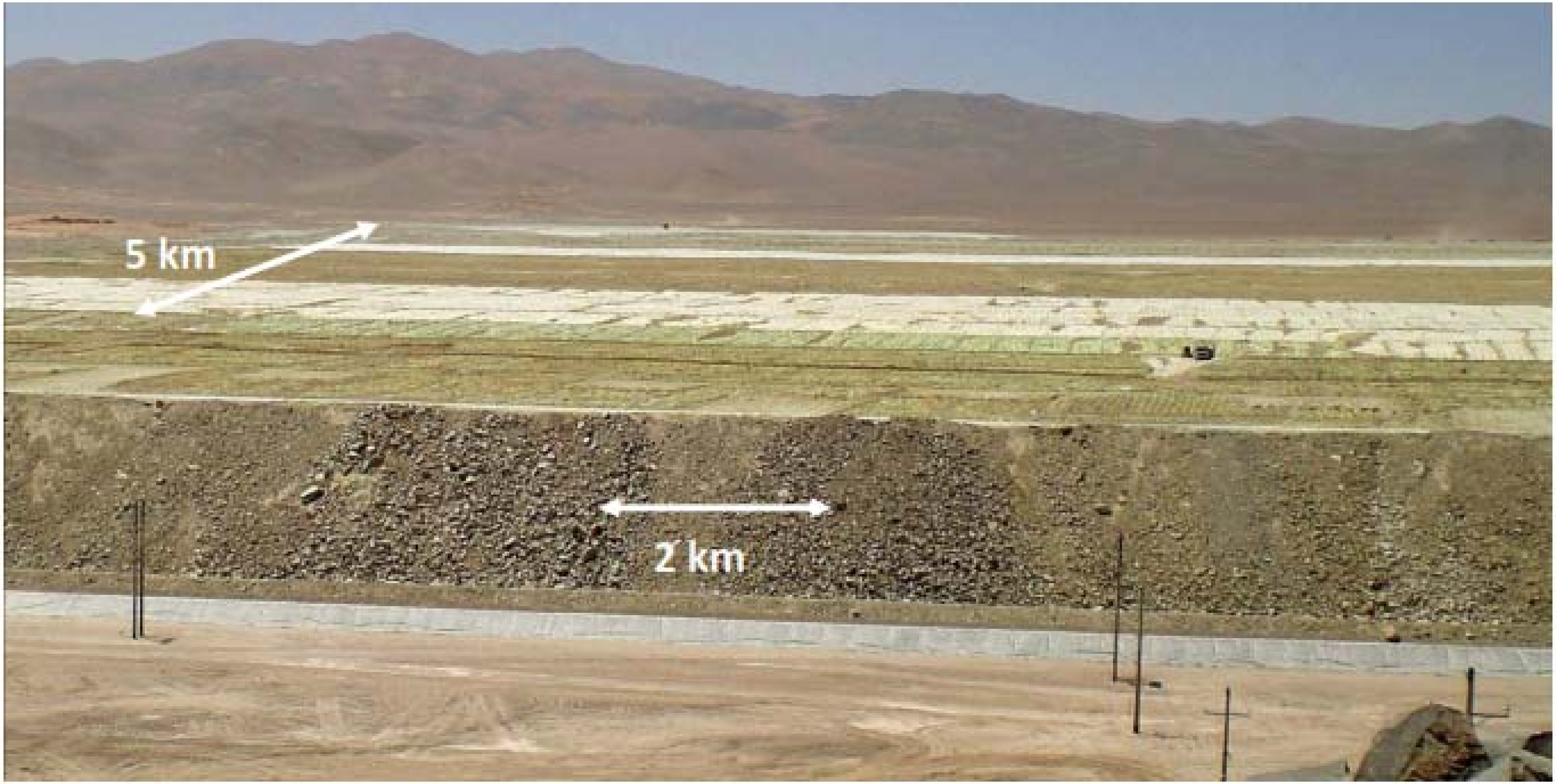


PLS stream

Cementation:

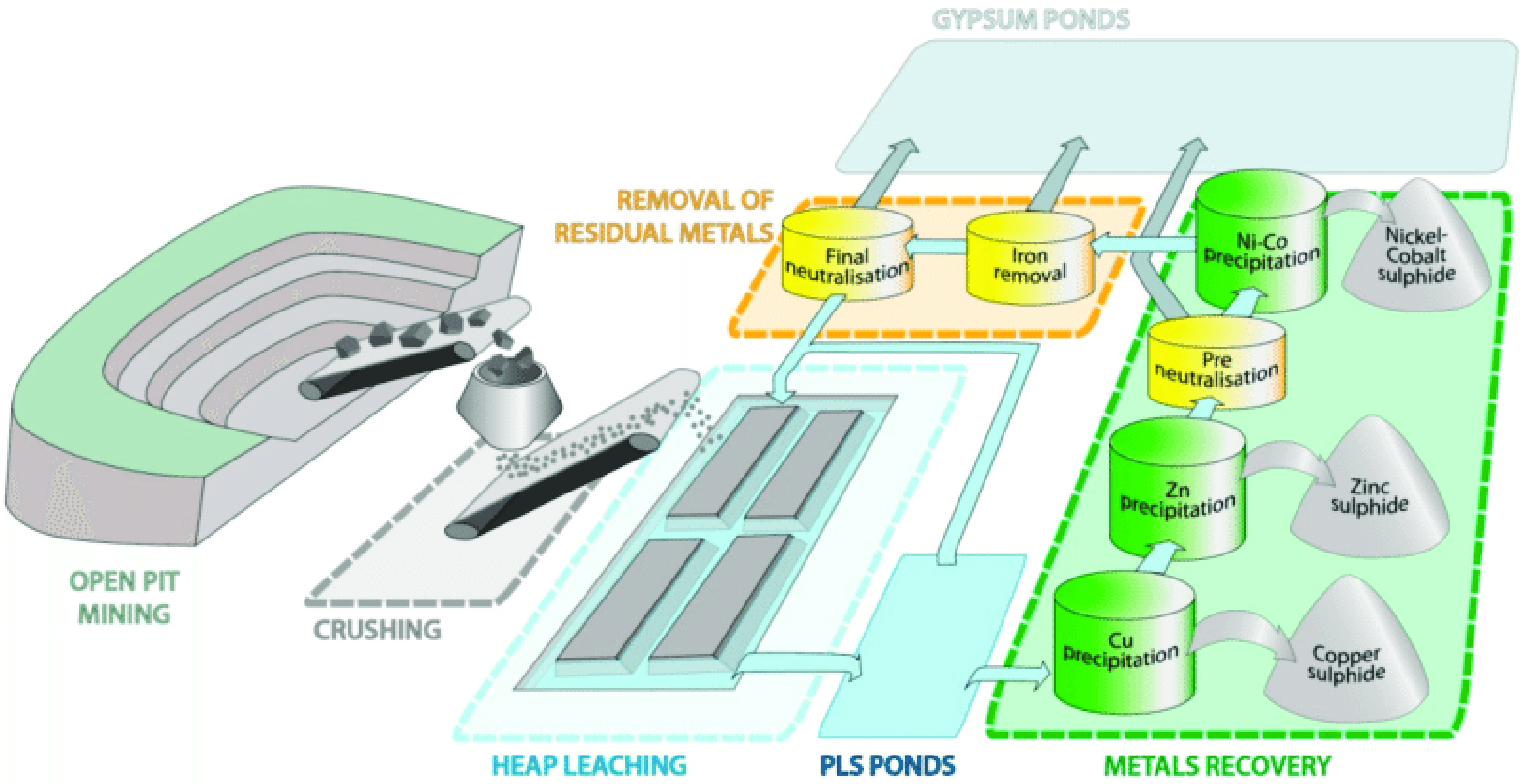
$Cu^{2+} + Fe^{0} \rightarrow Cu^{0} + Fe^{2+}$

# COPPER BIOHEAPLEACHING (CHILE)

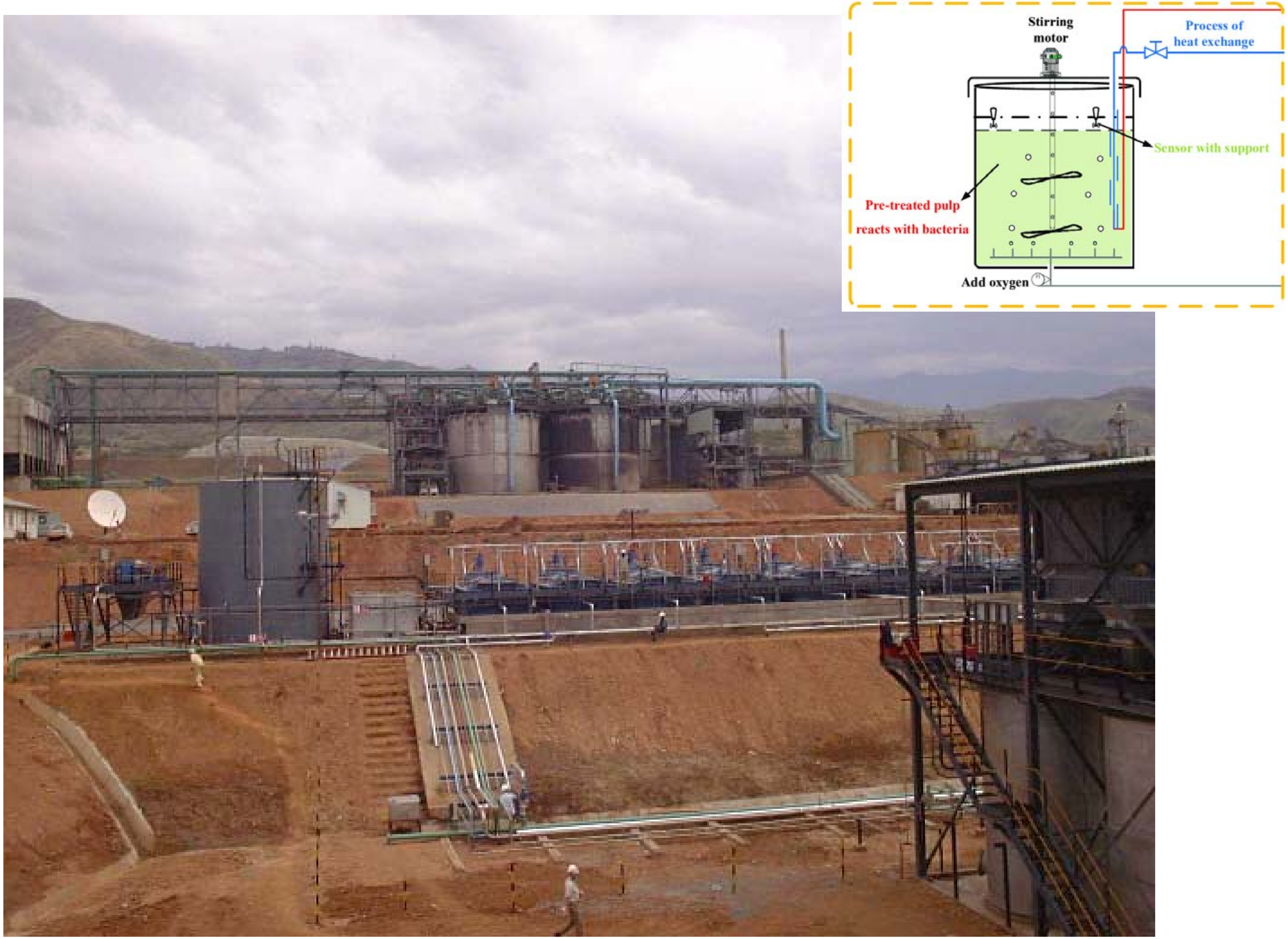



Escondida, copper mine, Chile

# NICKEL BIOHEAPLEACHING (Talvivaara Sotkamo Mine, Finland)

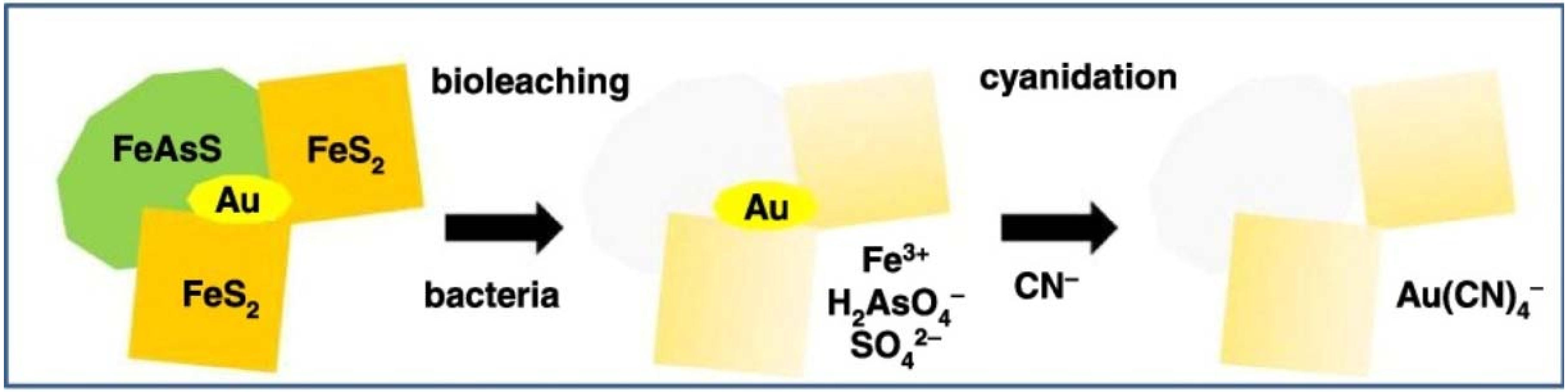


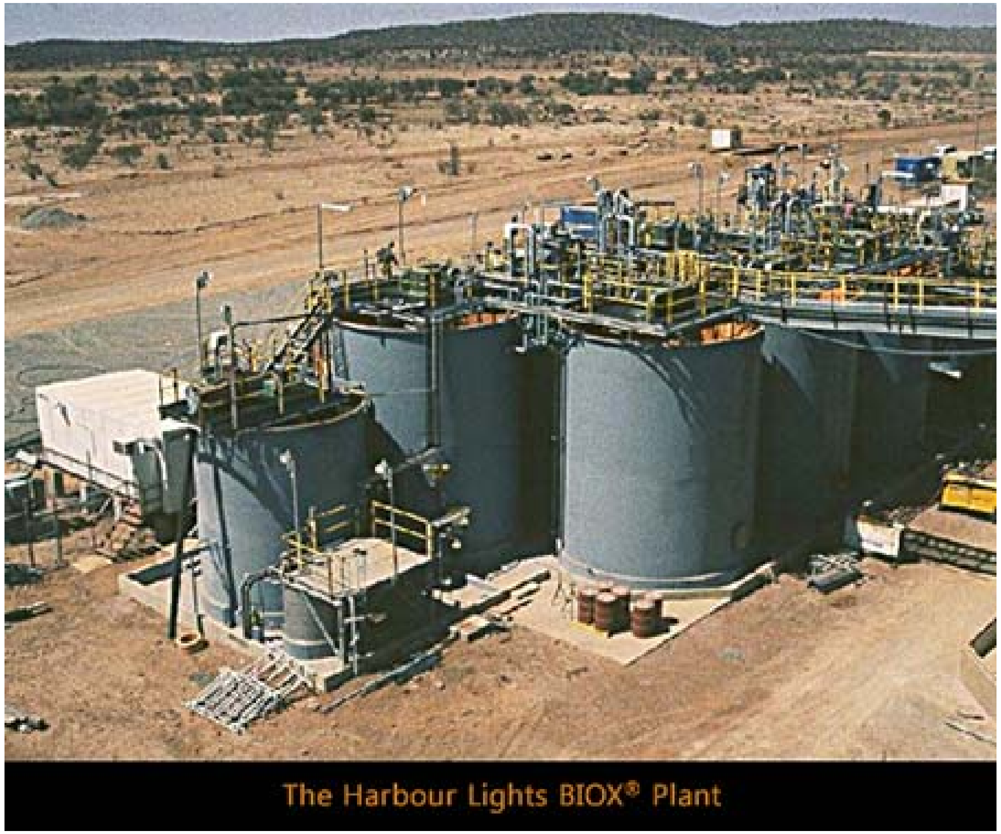

# COPPER BIOLEACHING IN TANK



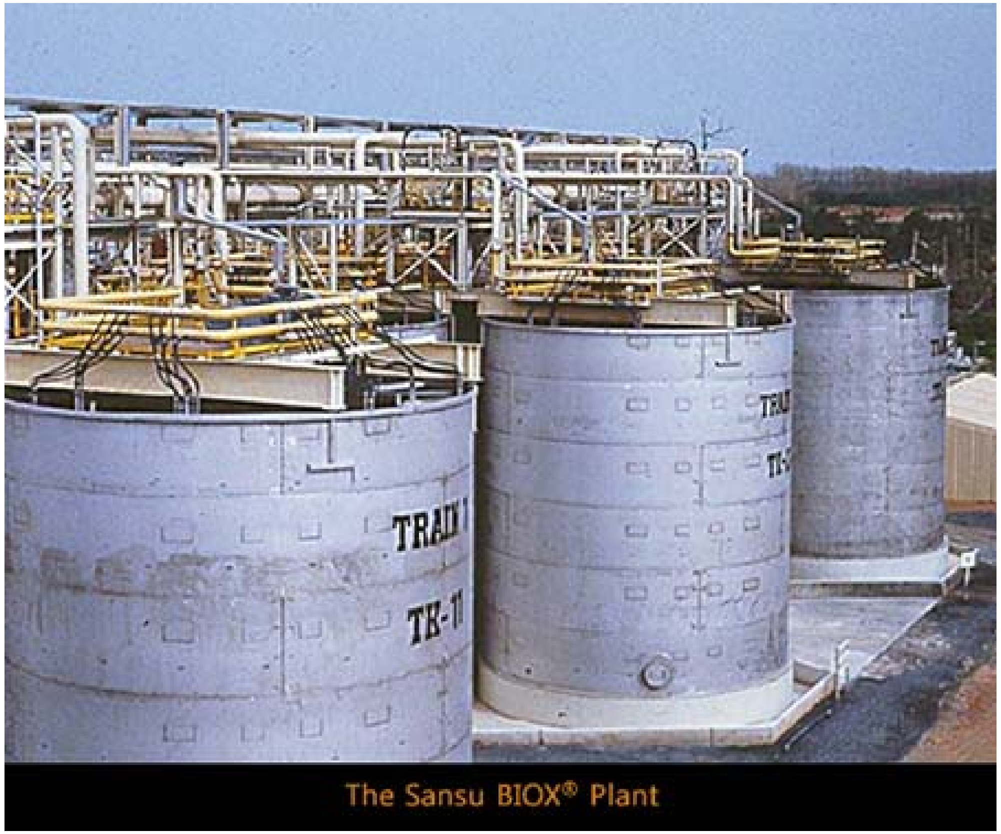

. Copper bioleaching industry in Uganda

# REFRACTORY GOLD ORE BIOLEACHING




Australia

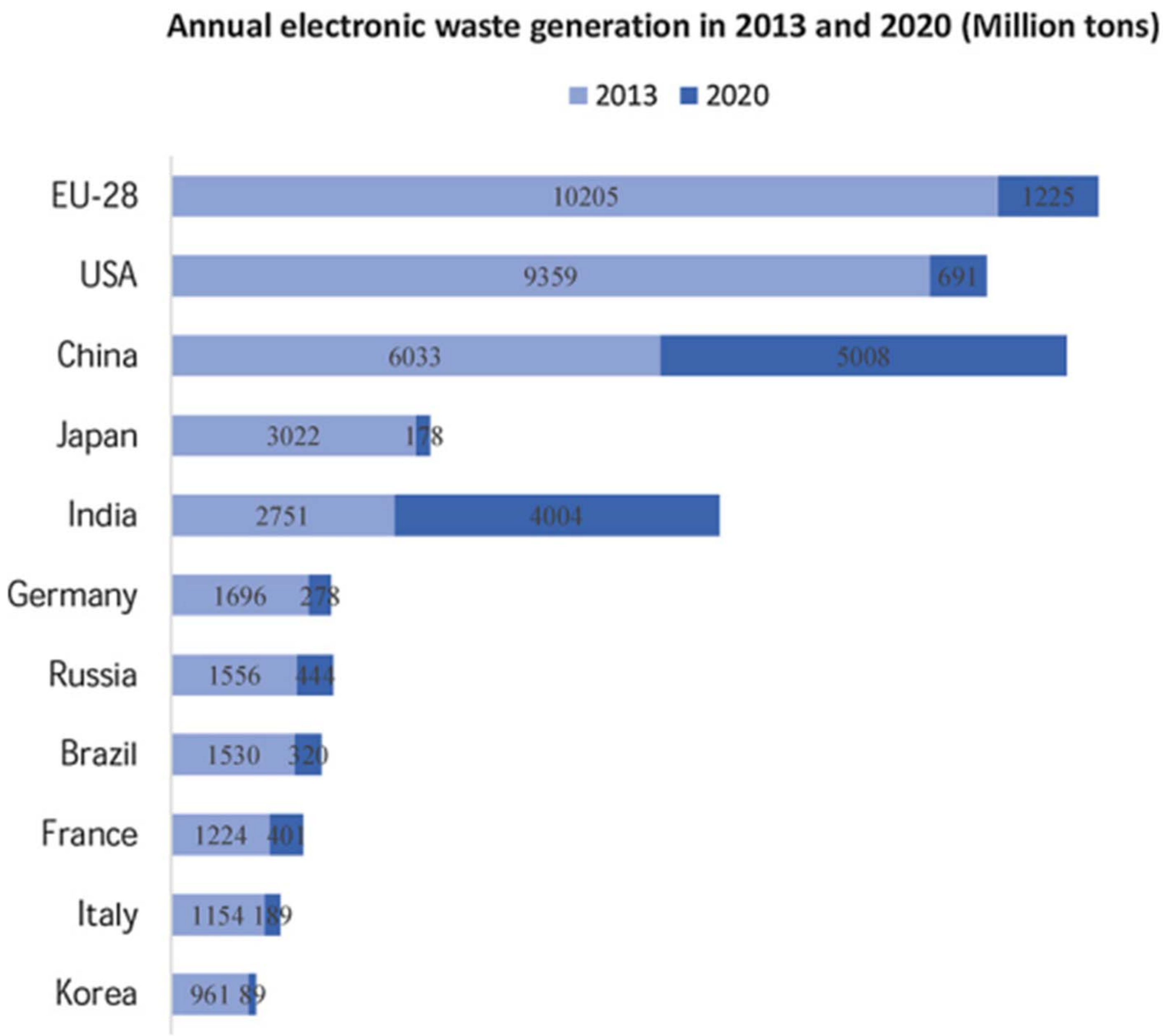



Ghana



http://overendstudio.co.za/websites/gold_fields_biox/biox/operations.html#

# METALS IN WASTE




Işıldar et al., 2019

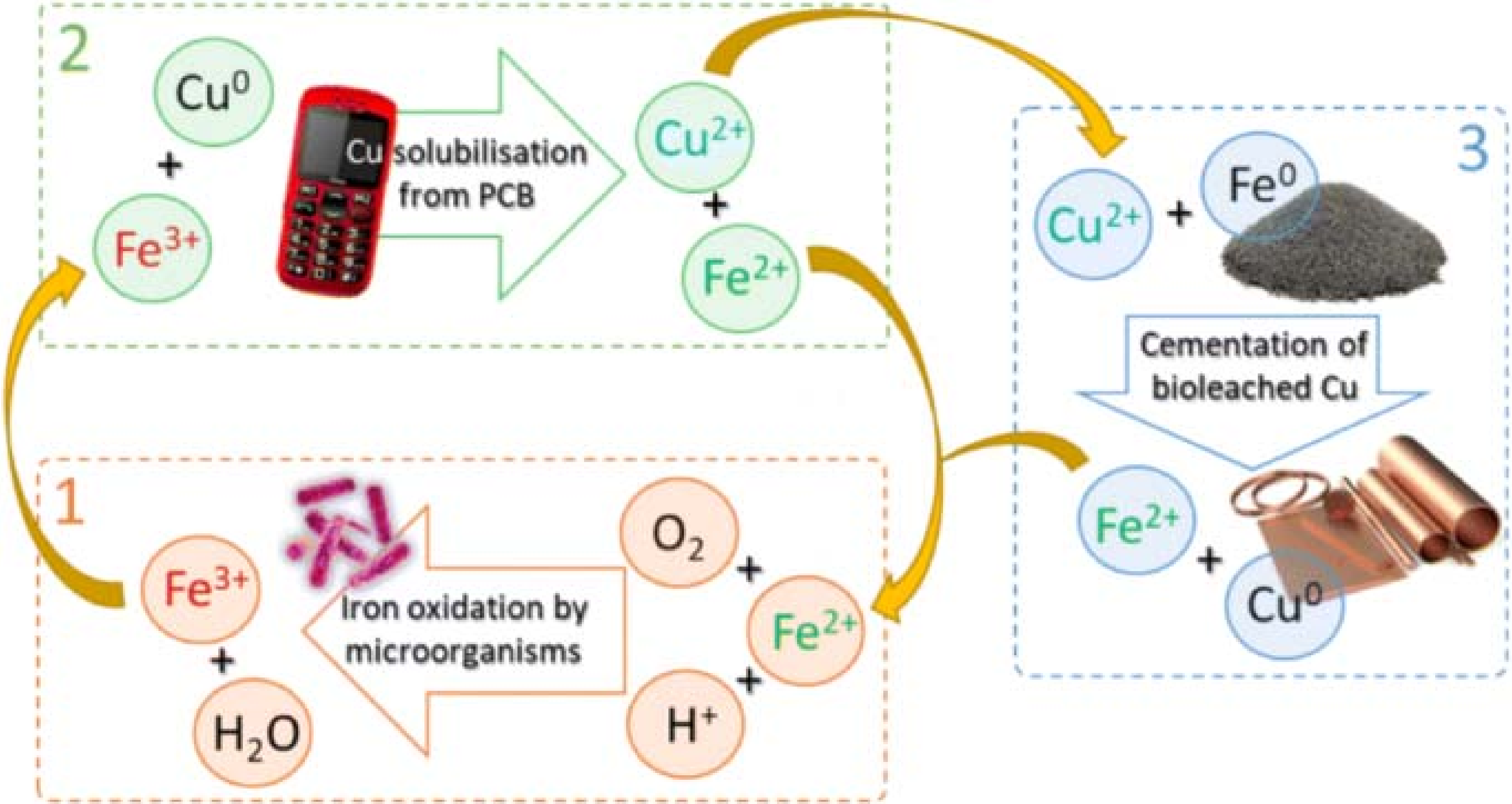
# APPLICATIONS OF MICROORGANISMS IN THE RECOVERY OF METALS FROM VARIOUS WASTE

| WASTE MATERIAL | METAL LEACHED | MICROORGANISMS |
|---|---|---|
| **Catalists** | Al, V, Mo, Ni, Co, Li | *Acidithiobacillus thiooxidans*<br>*Acidithiobacillus ferrooxidans*<br>*Aspergillus niger*[1]<br>*Penicillium simplicissimum*[1] |
| **Electronic scrap** | Al, Cu, Ni, Pb, Sn, Zn, Au | *Acidithiobacillus ferrooxidans*<br>*Acidithiobacillus thiooxidans*<br>*Aspergillus niger*[1]<br>*Penicillium simplicissimum*[1]<br>*Cromobacterium violaceum*[2]<br>*Sulfobacillus thermosulfidooxidans*[3] |
| **Municipal solid waste Fly ash** | Al, Fe, Mn, Ni, Cd, Cr, Cu, Ni, Pb, Zn | *Acidithiobacillus thiooxidans*<br>*Acidithiobacillus ferrooxidans*<br>*Pseudomonas putida*[4]<br>*Bacillus megaterium*[5]<br>*Aspergillus niger*[1]<br>*Acidianus brierleyi*[6] |
| **Spent battery waste** | Li, Co | *Acidithiobacillus spp.* |
| **Belt filter press solids** | Cu | *Acidithiobacillus ferrooxidans* |
| **Sewage sludge** | Cu, Mn, Zn, Ni, Cd, Cr, Pb | *Acidithiobacillus thiooxidans* |
| **Tannery sludge** | Cr | *Acidithiobacillus thiooxidans* |
| **Jewelry waste/ Automobile catalyst** | Ag, Pt, Au | *Cromobacterium violaceum*[2],<br>*Pseudomonas fluorescens*[4] |



BHARADWAJ Y TING, 2011; KUCUKER Y KUCHTA, 2018

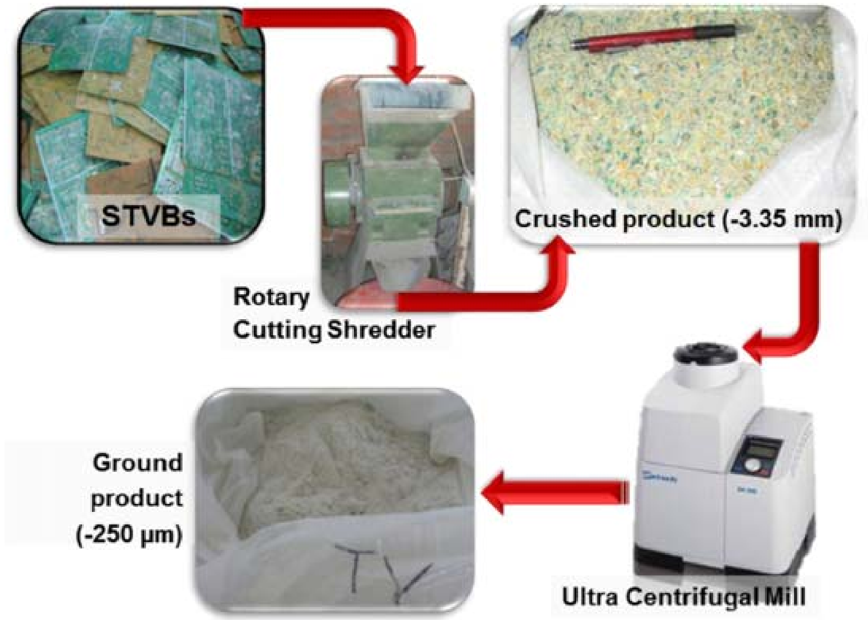
# COPPER RECOVERY FROM E-WASTES

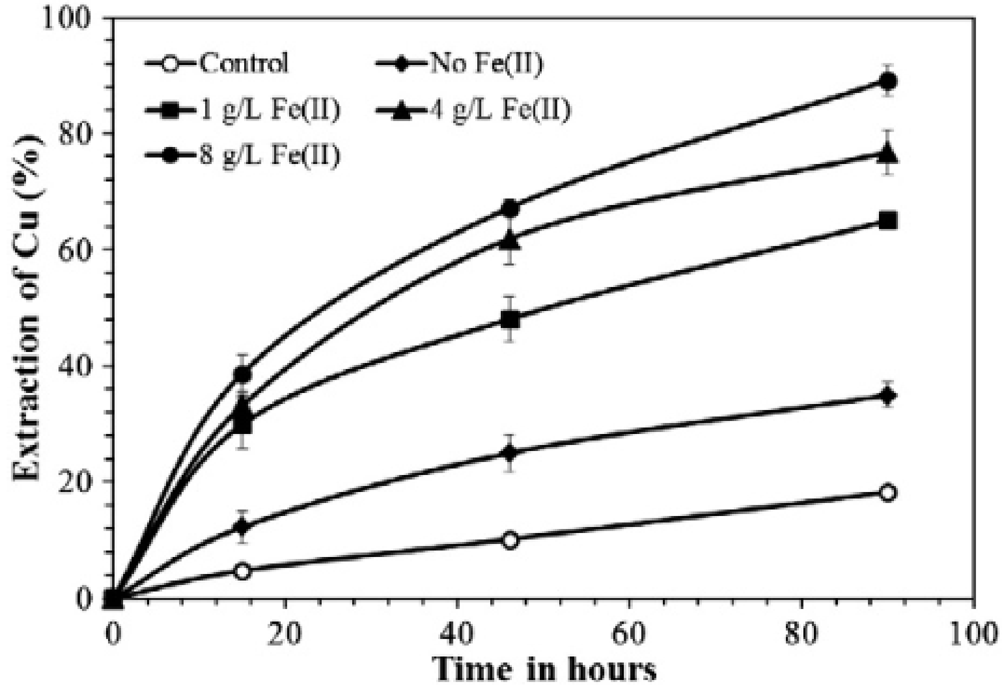





BENZAL ET AL., 2020

# EXAMPLE: COPPER BIOLEACHING USING TV WASTE



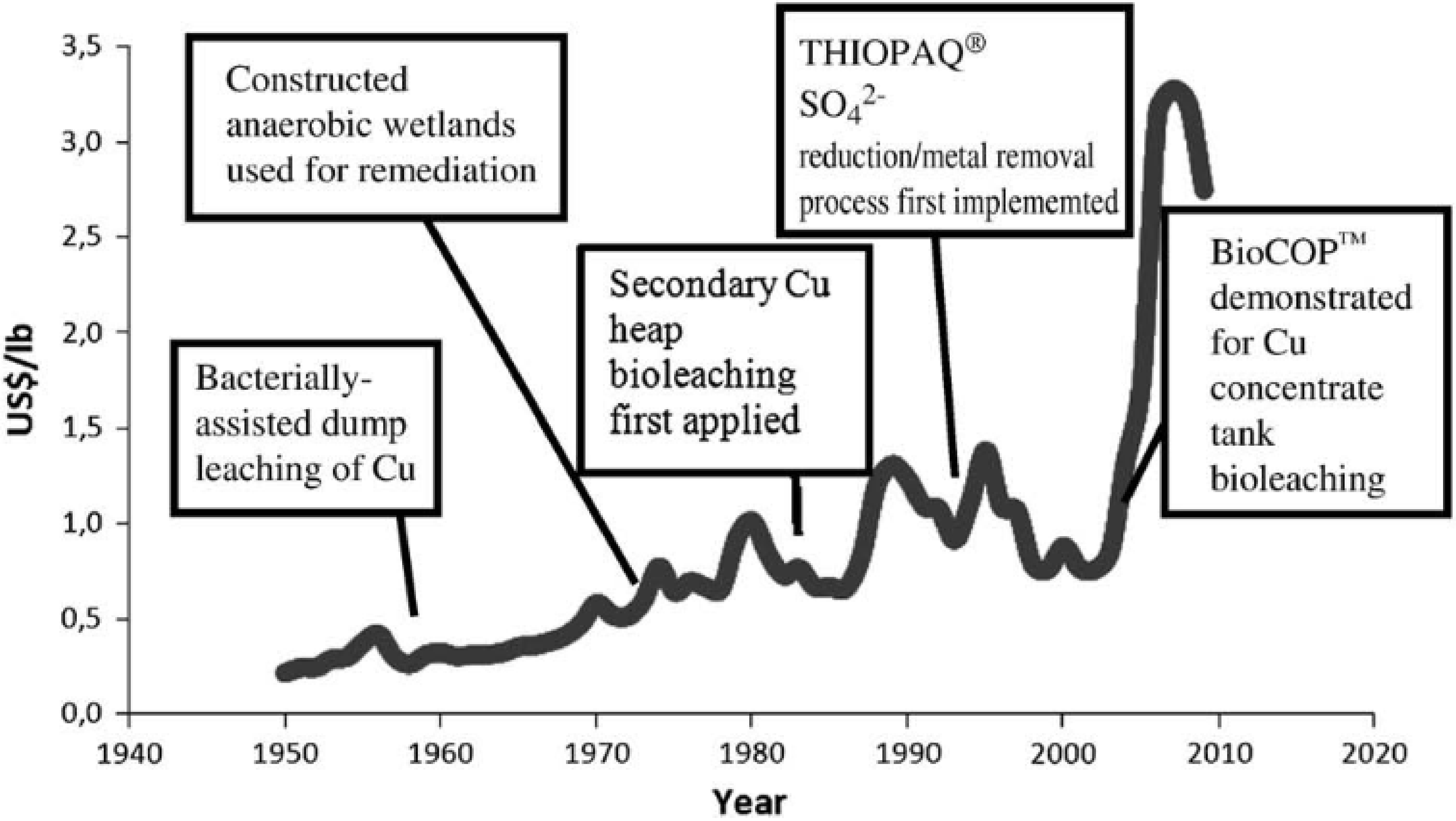

$$2Fe^{2+} + {}^{1}/{}_{2}\,O_2 + H^+ \xrightarrow{\text{bacteria}} 2Fe^{3+} + H_2O$$

$$Cu^0 + 2Fe^{3+} \rightarrow Cu^{2+} + 2Fe^{2+}$$



Bas et al., 2013

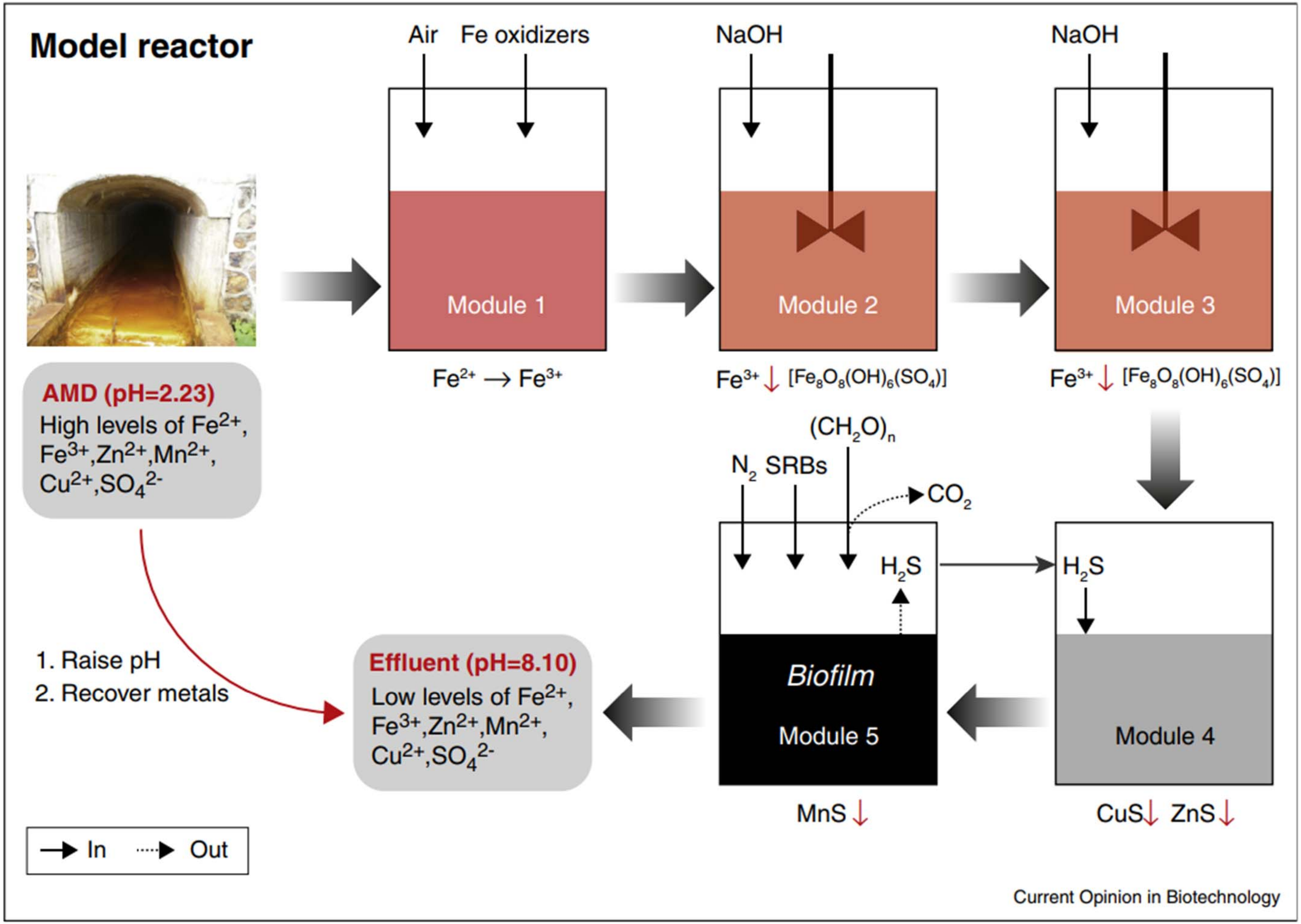
# BIOMETALLURGY AS AN ALTERNATIVE



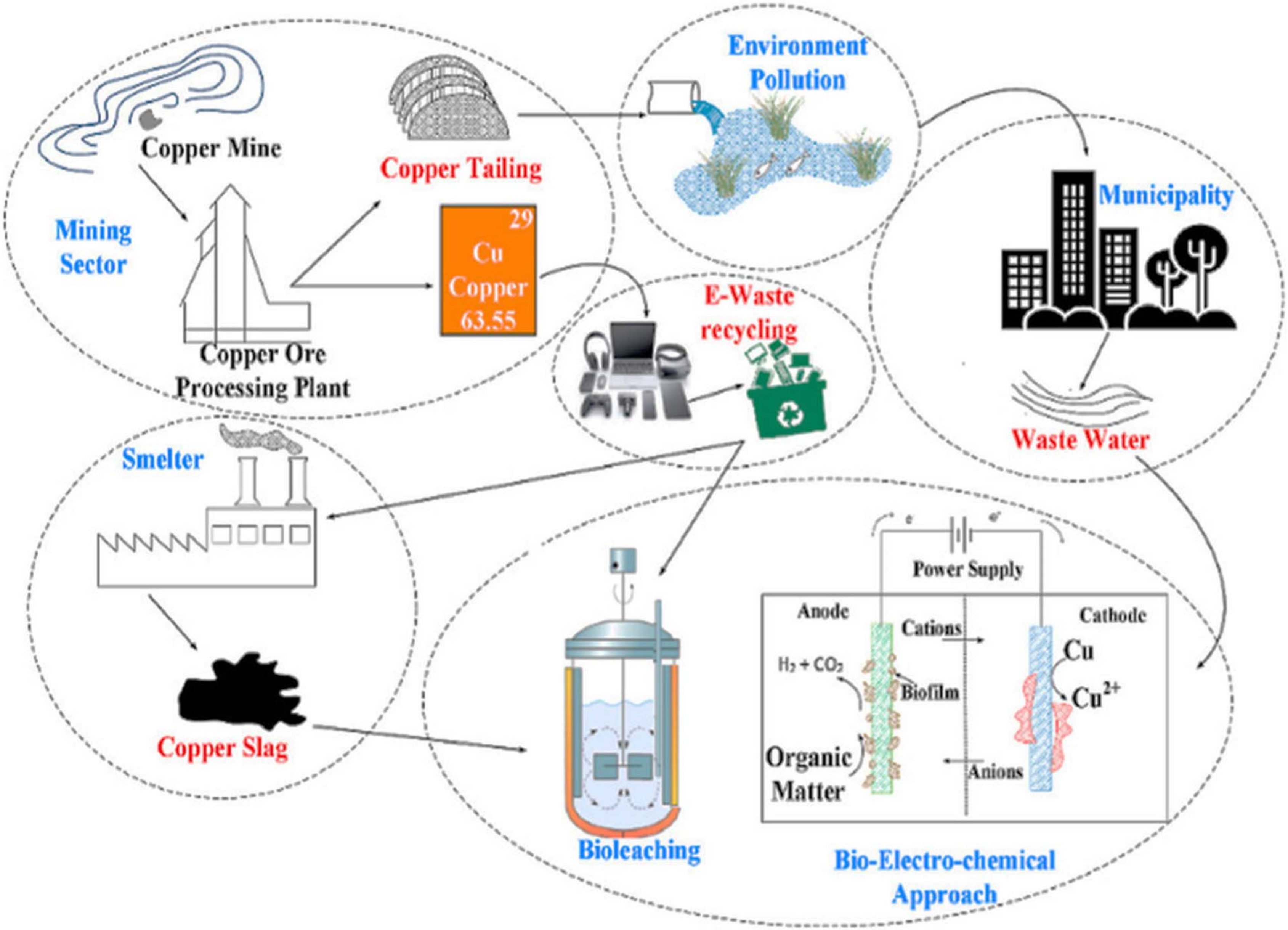



Batty y Rorke, 2006

# BIOREMEDIATION OF POLLUTED SOILS AND WATERS



# INTEGRATED BIOLEACHING-ELECTROMETALLURGY FOR COPPER RECOVERY

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Thanks for your attention