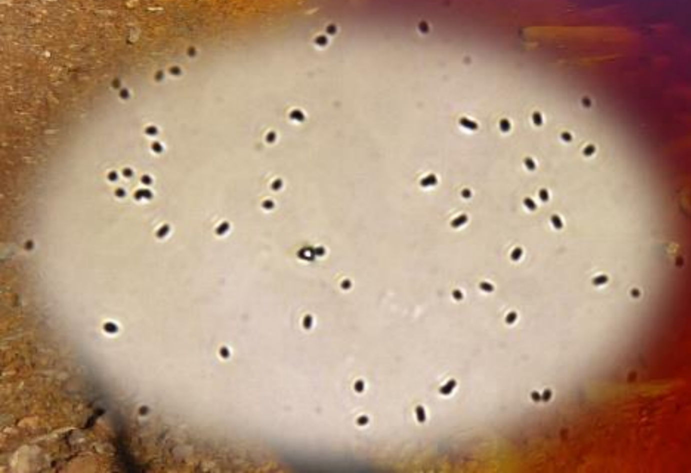
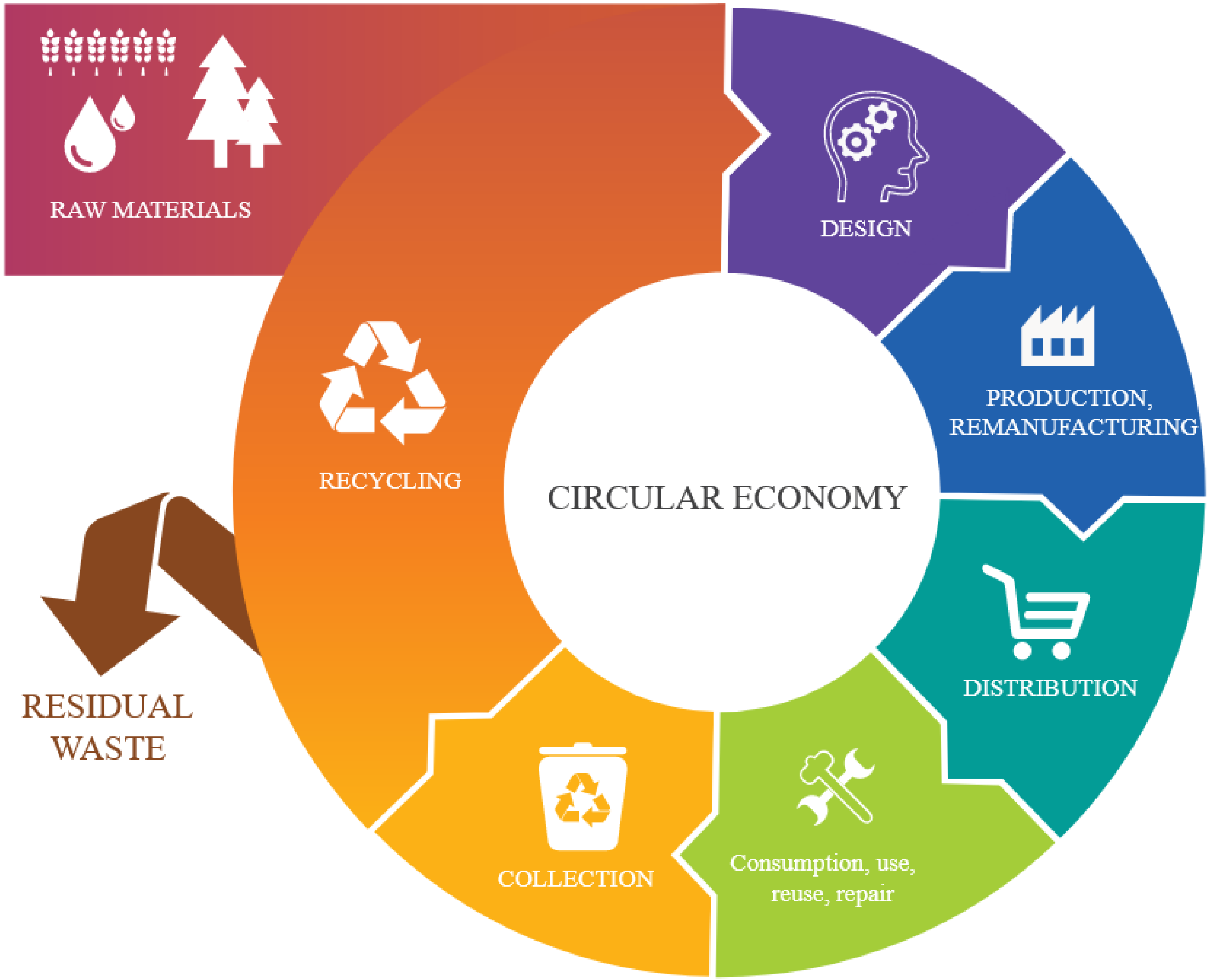
HEI4S3-RM
Building Ecosystem Integration Labs at HEI to foster Smart Specialization and Innovation on Sustainable Raw Materials
Supported by EIT RawMaterials Connecting matters
Funded by the European Union
EIT HEI Initiative – Innovation Capacity Building for Higher Education – eit-hei.eu

COPPER BIOMETALLURGY: EXTRACTIVE PROCESSES USING BACTERIA



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

21/12/2022



European Parliament.
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.

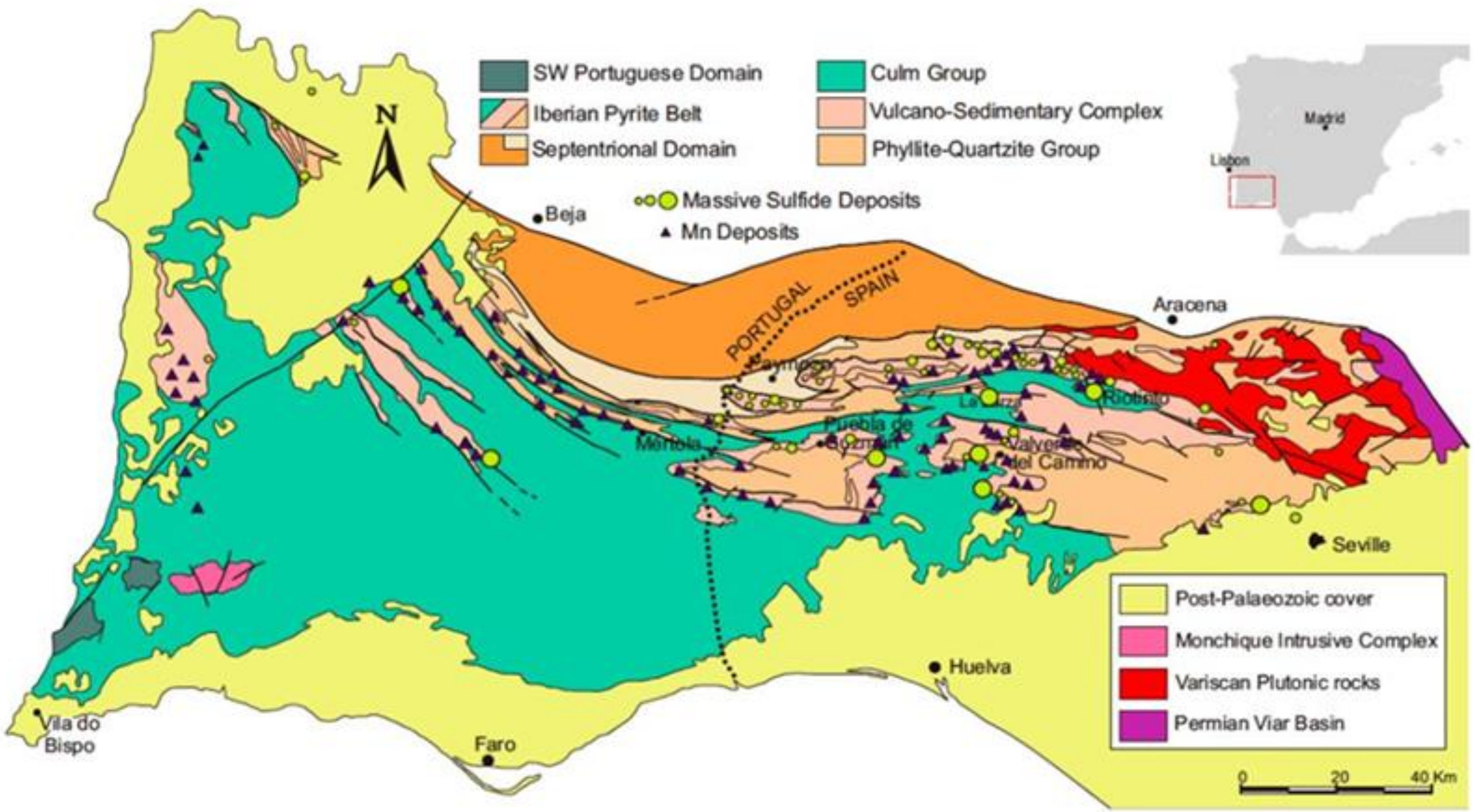
(4) Recognize the possible applications of such bacteria in copper metallurgy.

(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

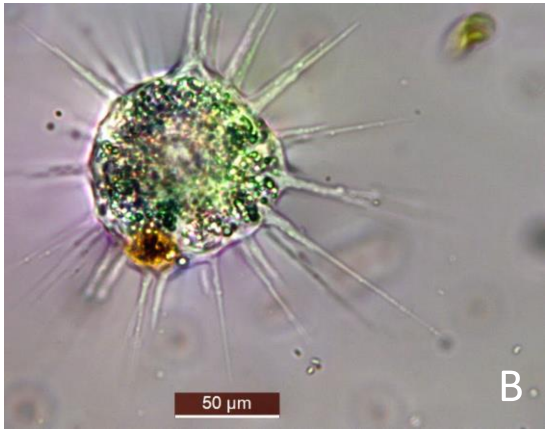
Fe_3^{+}

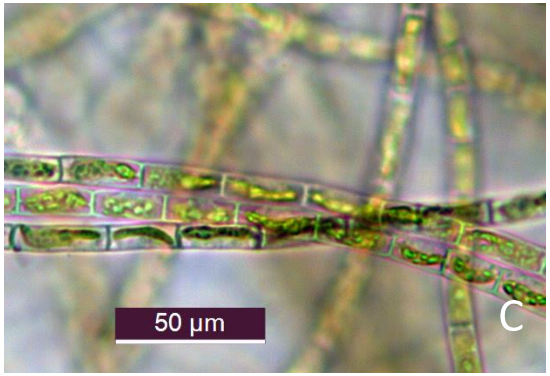
$$4FeS_2 + 15O_2 + H_2O \rightarrow 4Fe^{3+} + 8SO_4^{2-} + 4H^+$$ *Bacteria*

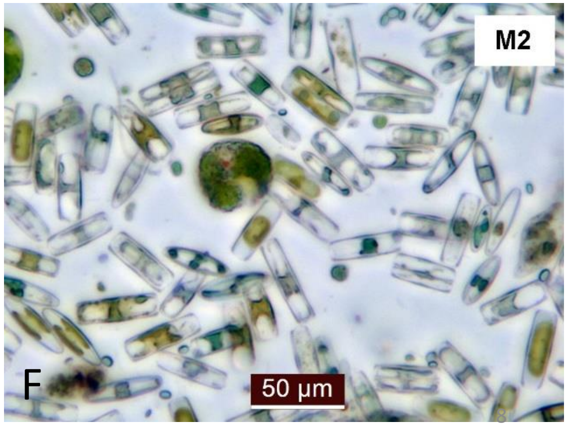
$$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+$$

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

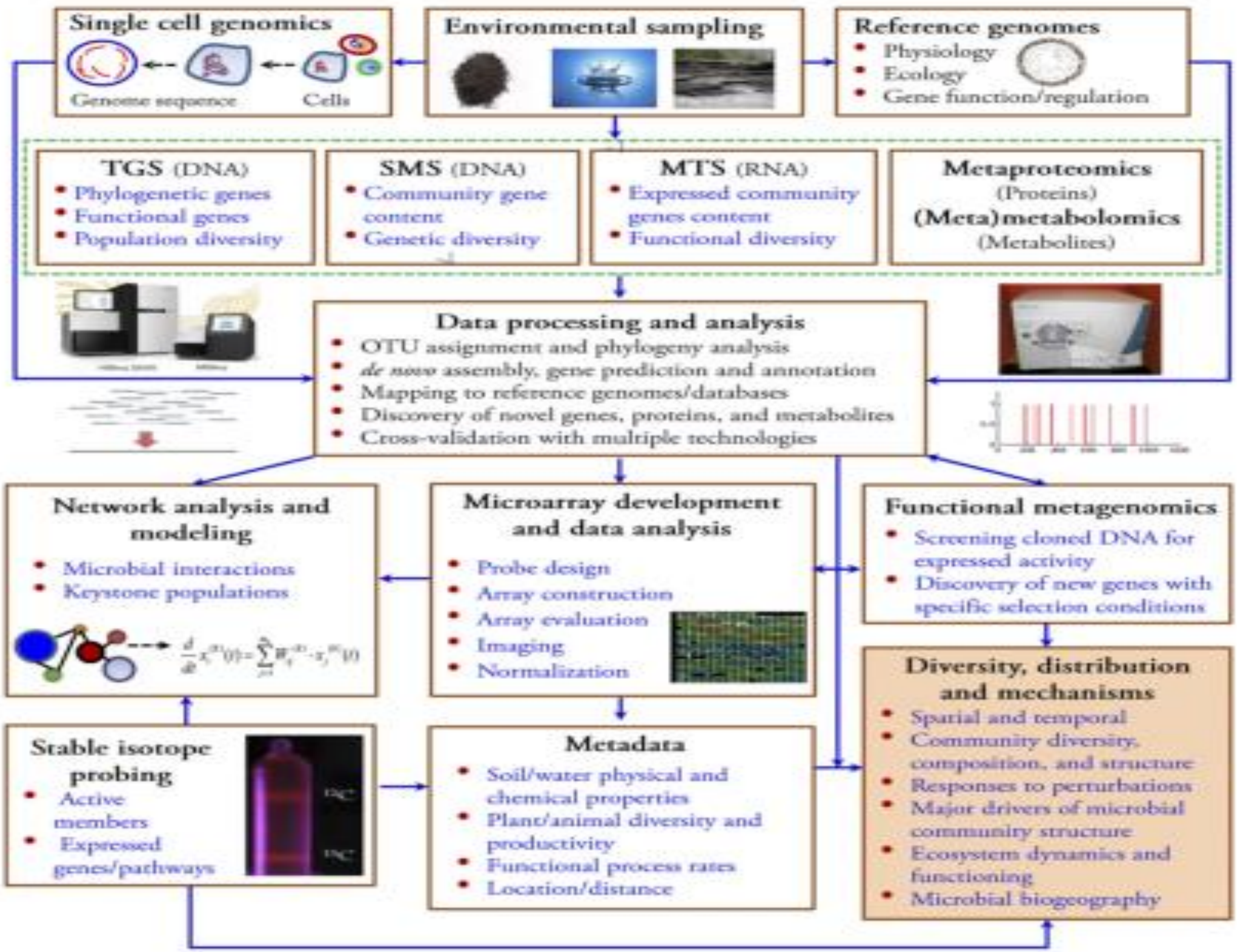
MICROORGANIMS OF AMD RIVERS







METAGENOMIC ANALYLIS

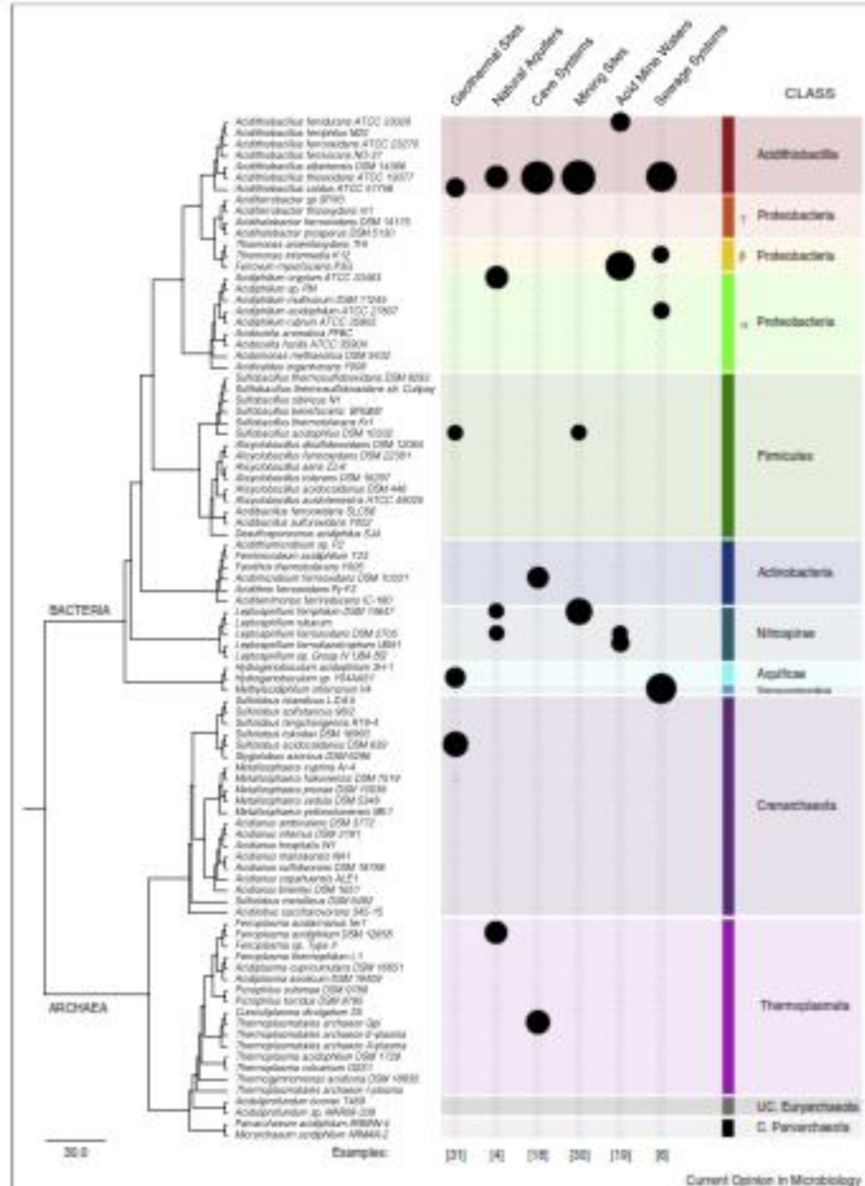


Zhou et al., 2015; https://mbio.asm.org/content/6/1/e02288-14/F1

THE DIVERSITY OF BACTERIA IS EXTRAORDINARY

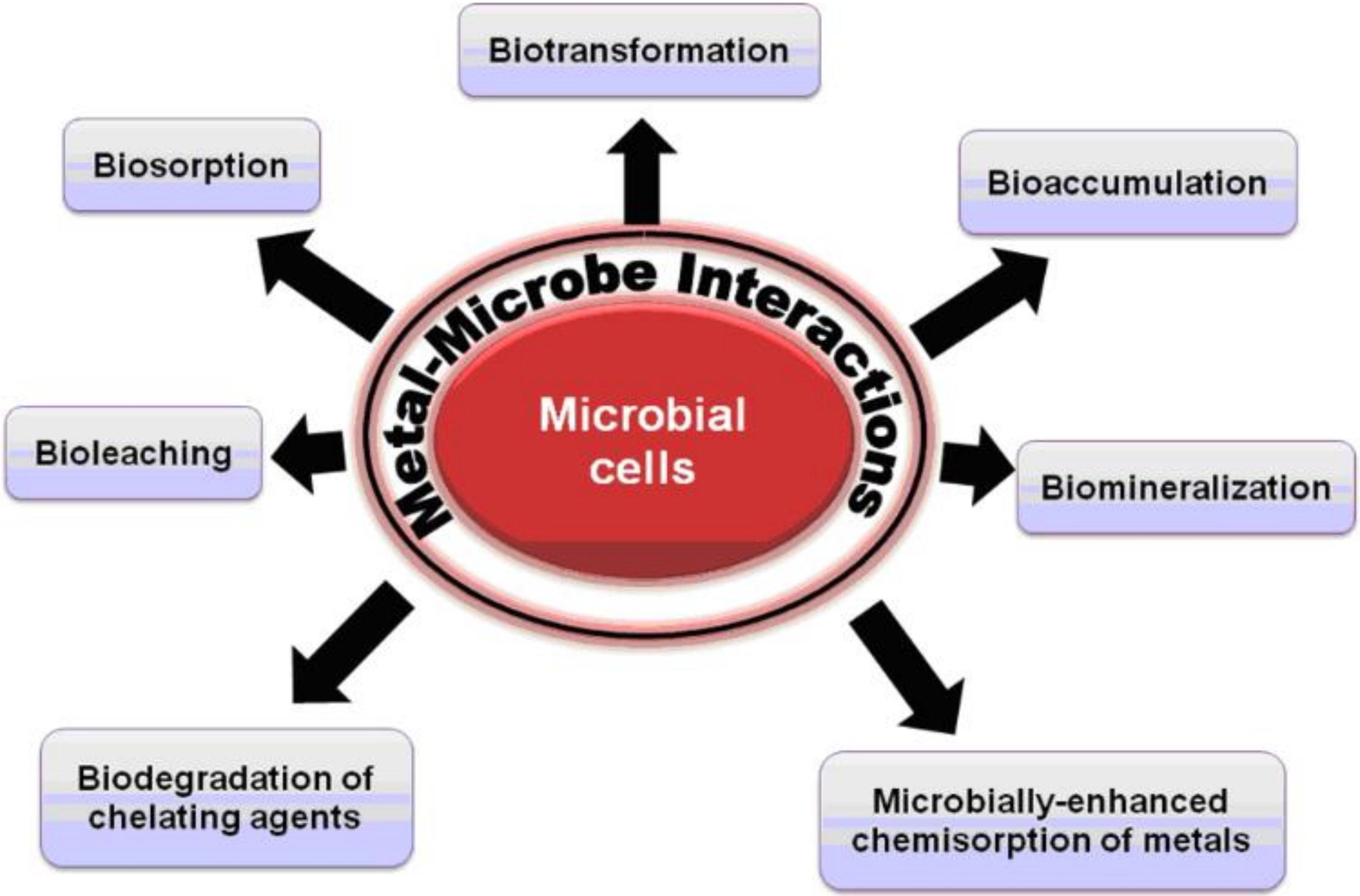
Iron-oxidizing acidophiles	**Iron-reducing acidophiles**	**Iron-oxidizing/reducing acidophiles**
BACTERIA		
Leptospirillum (L.)[1]	*Acidiphilium (A.)*[2/3]	*Acidithiobacillus (At.)*[1]
L. ferrooxidans	*A. cryptum*[2]	*At. ferrooxidans*
L. ferriphilum	*A. acidophilum*[3]	*At. ferrivorans*
"L. ferrodiazotrophum"	*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.*



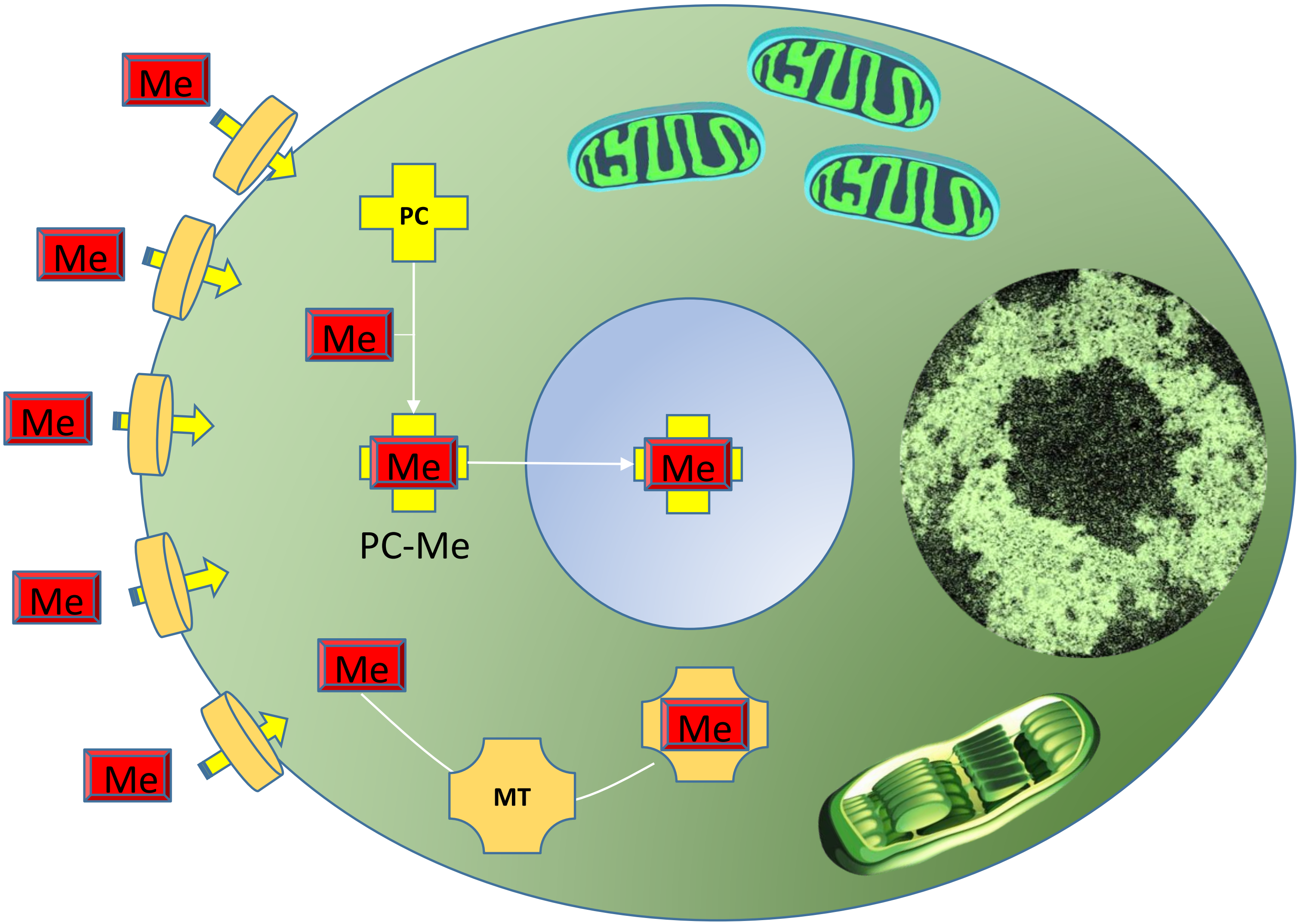
Johnson et al., 2012; Quatrini y Johnson, 2018

METAL-BACTERIA INTERACTIONS



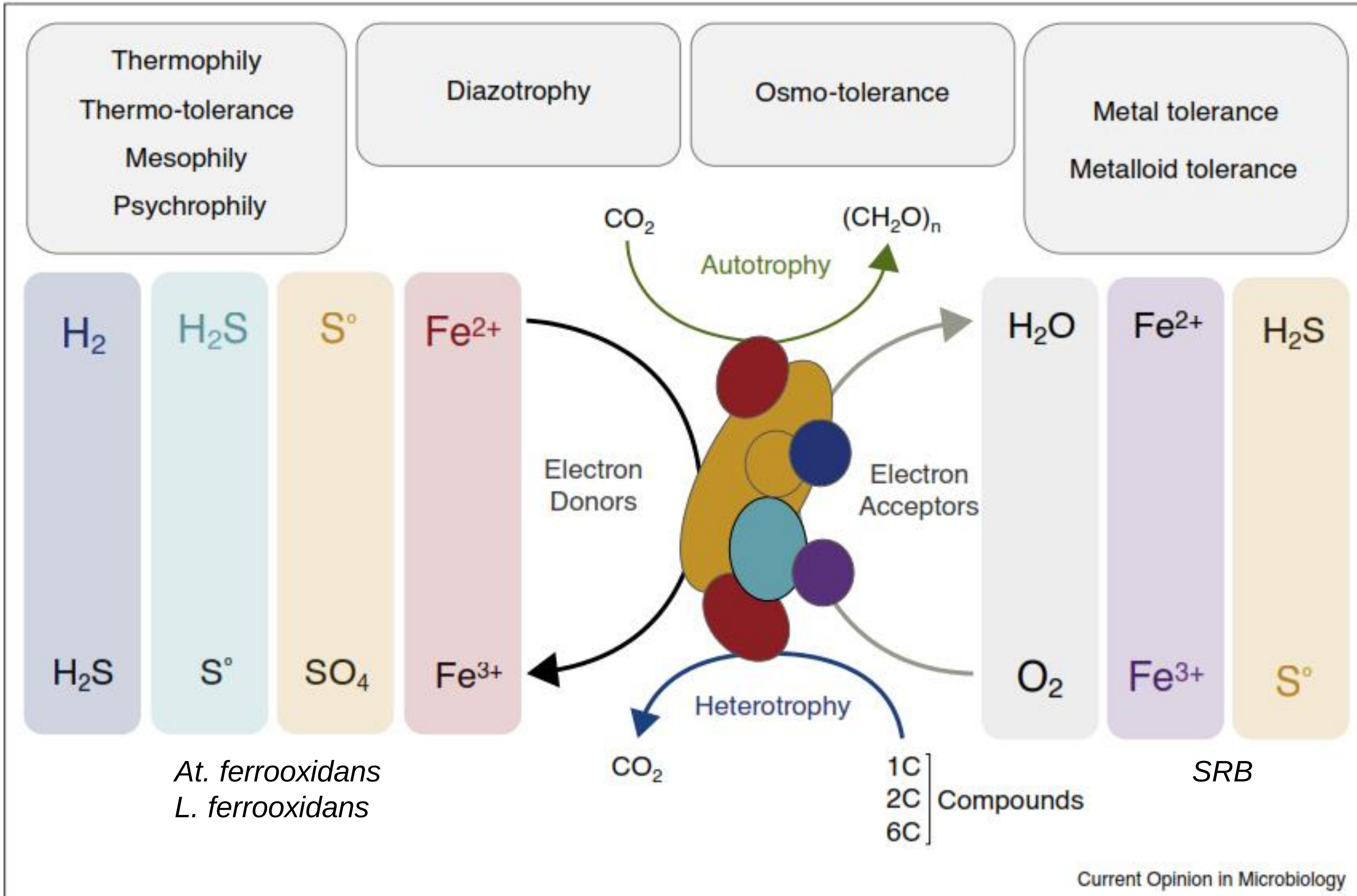
Tabak et al., 2005; Ahemad, 2012

METAL-ALGAE INTERACTIONS



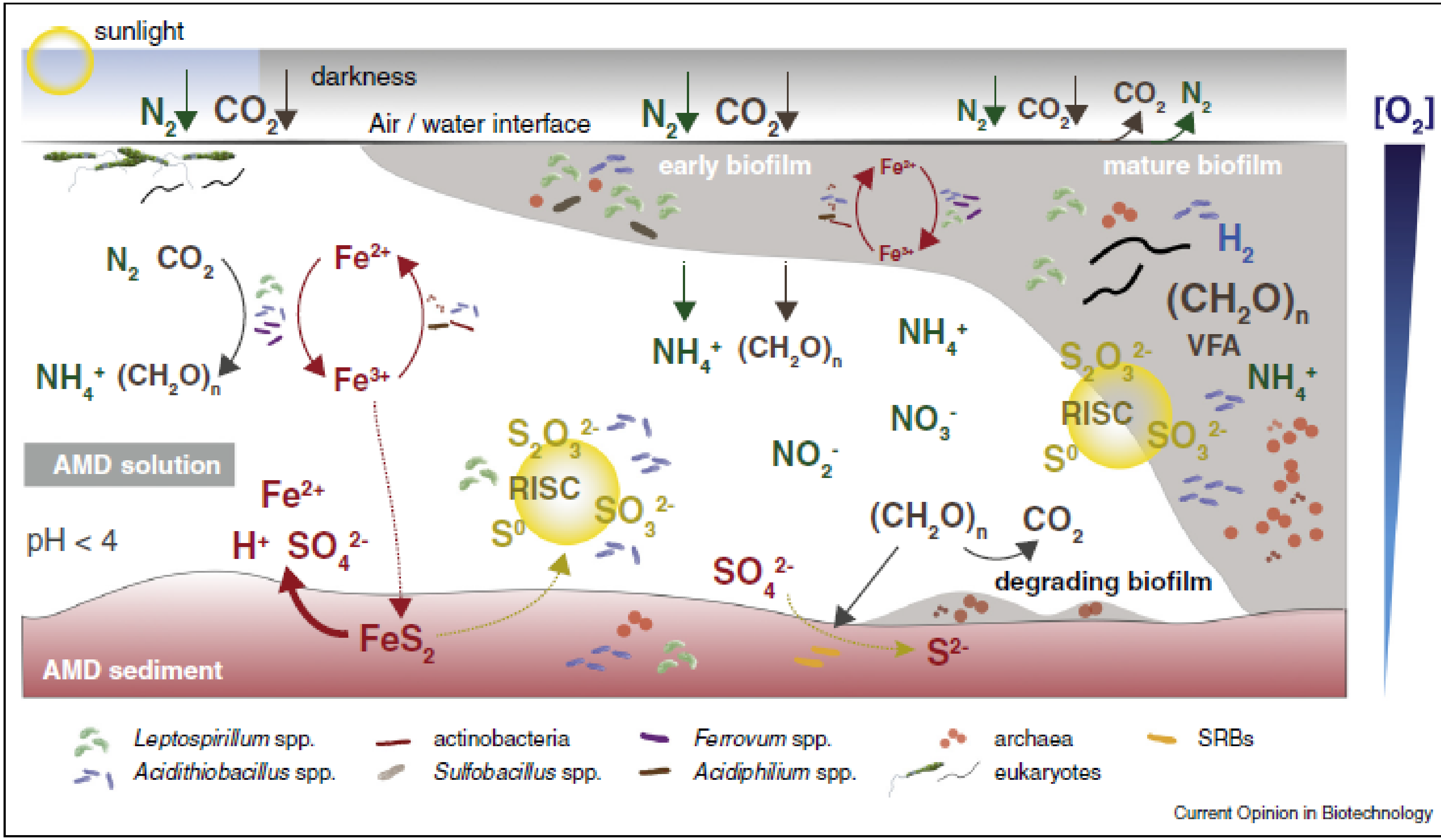
(based on Aguilera et al, 2020)

CHEMOLITOTROPHIC AND HETEROTROPHIC BACTERIA



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

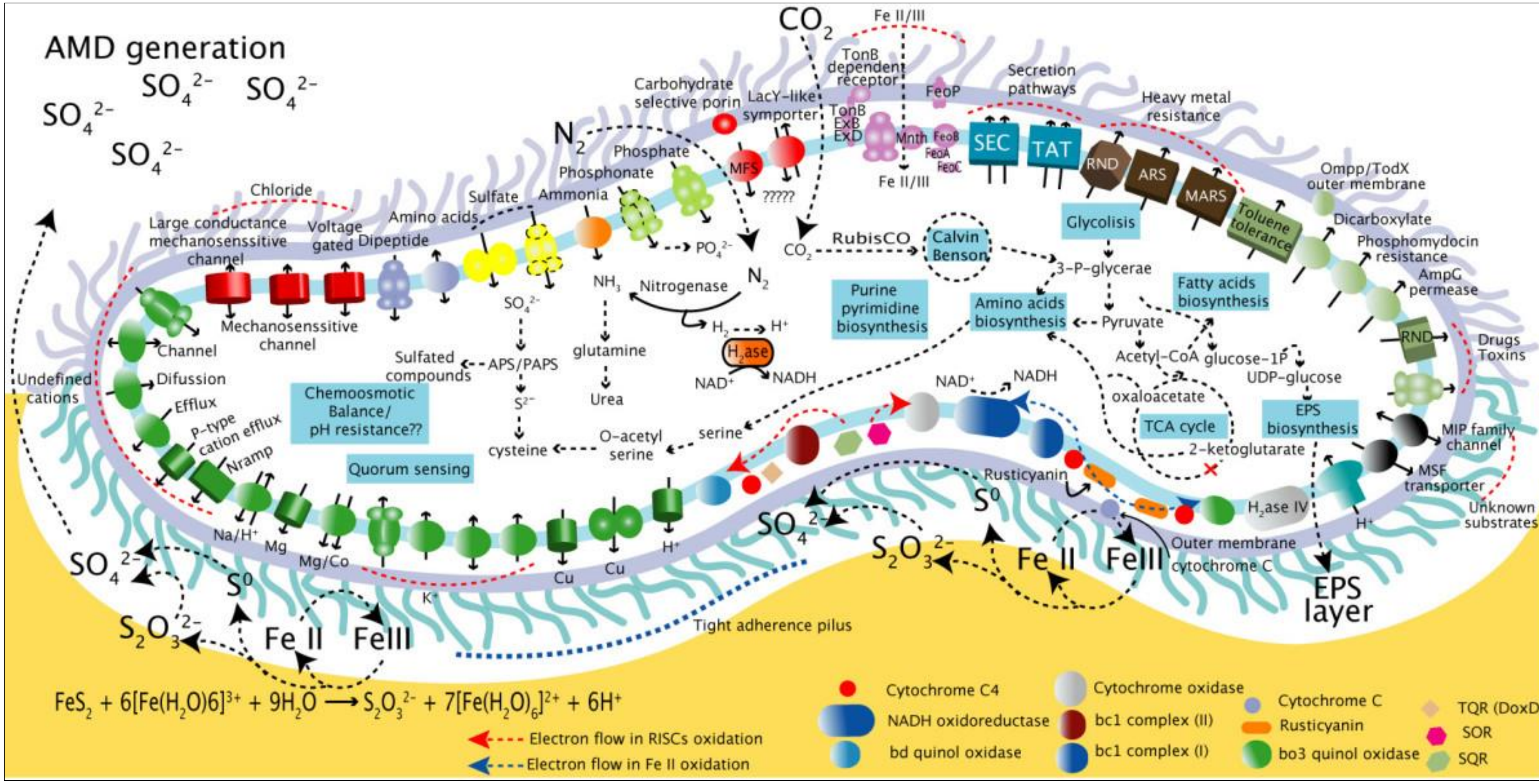
BACTERIAL ENVIRONMENTS IN AMD-POLLUTED WATERS

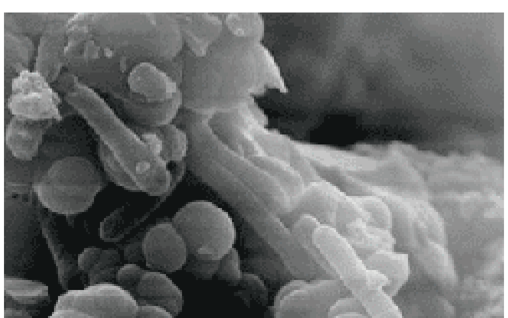


3 environments are considered: air/water interface, biofilms and sediments. Auto- and diazotrophic bacteria fix CO2 and N2 through reduction coupled with oxidation of Fe(II). Redox reactions carried out by lithotrophic bacteria that consume metal sulfides (RISC) are carried out through the formation 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

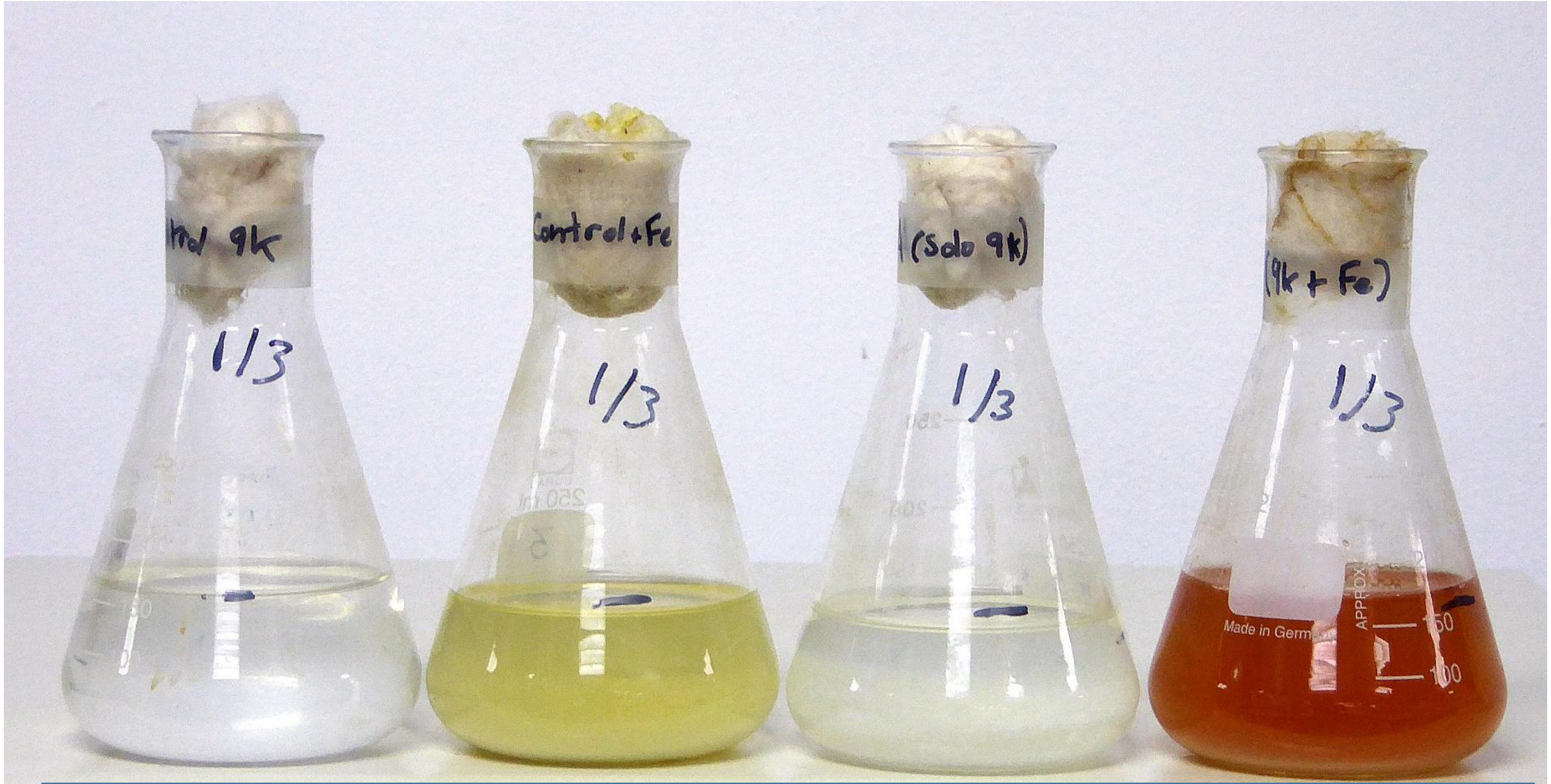
SAMPLING OF BACTERIA IN AMD-POLLUTED RIVERS

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

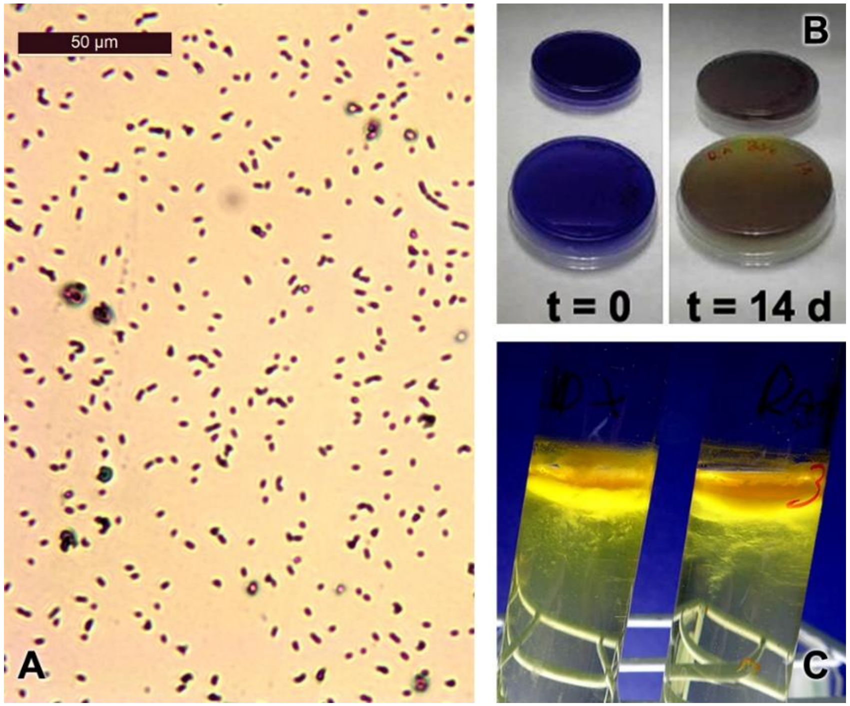
1. GROWING BACTERIA AND REPRODUCING AMD

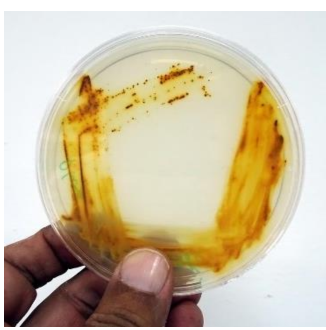


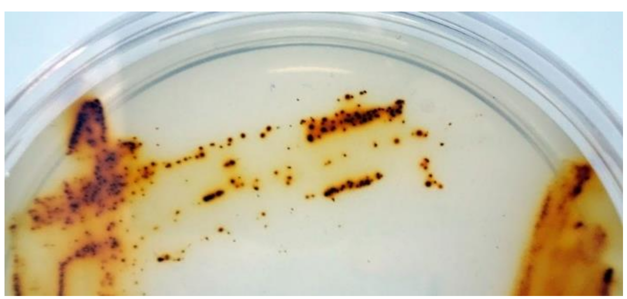
Only 9K	9K + Fe^{2+}	9K + bacteria	9K + Fe^{2+} + bacteria

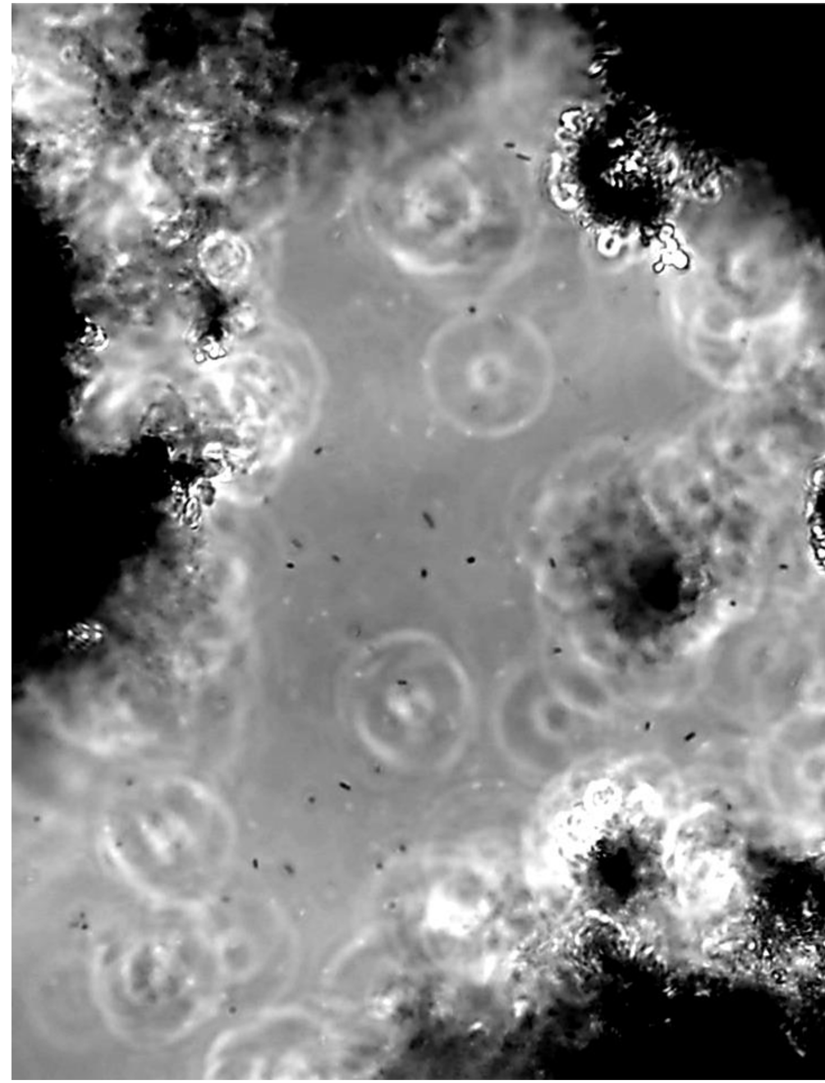
Inoculum: consortium of bacteria from AMD-polluted river. Specific growth medium: 9K. Source of iron: $FeSO_4$

2. TESTING THE PRESENCE OF BACTERIA

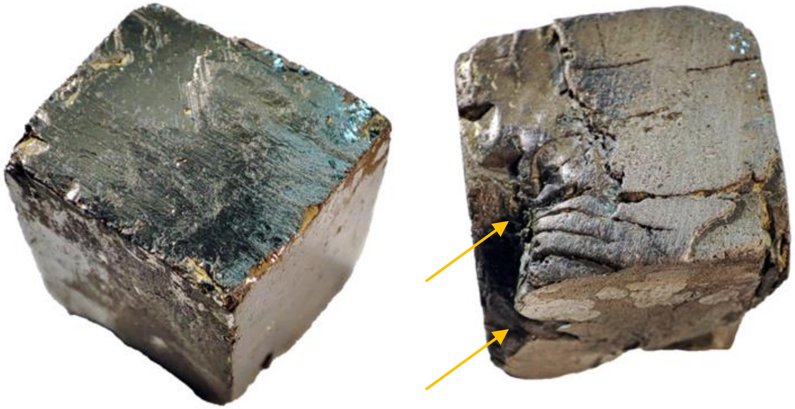






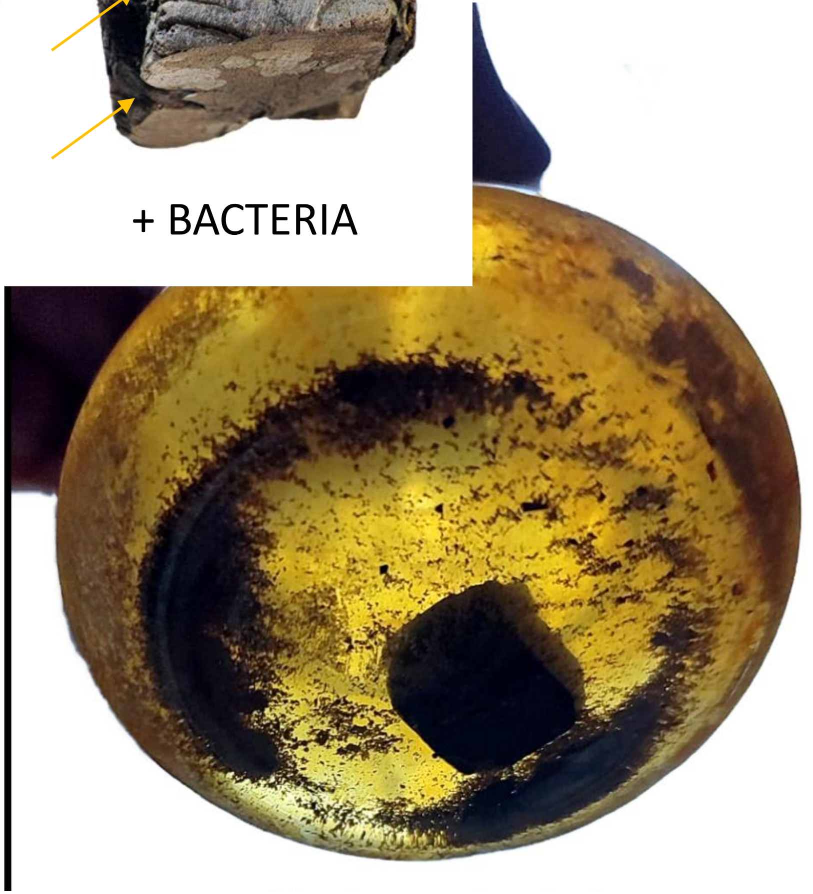


3. TESTING BIOLEACHING OF PYRITE



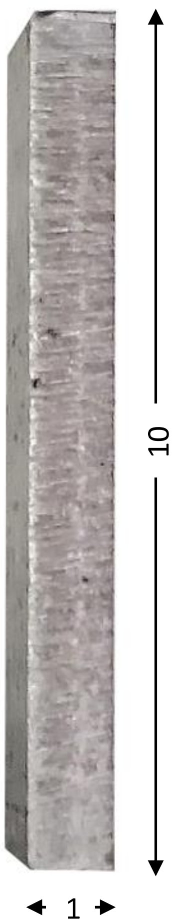
- BACTERIA + BACTERIA

STERILE MEDIUM (WITHOUT BACTERIA)



MEDIUM WITH BACTERIA

4. TESTING BIOCORROSION OF CARBON STEEL

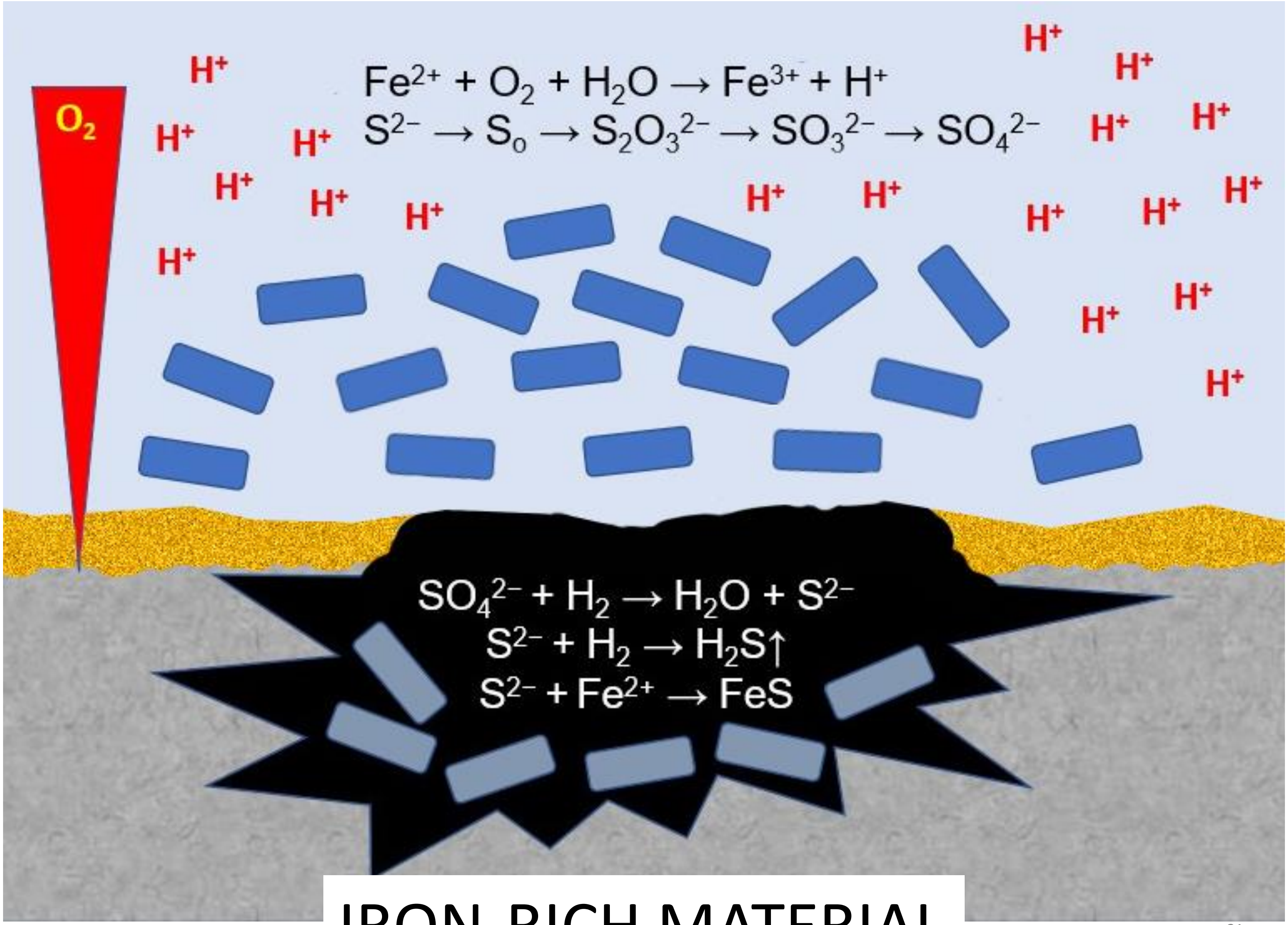


Carbon steel test tube (10x1 cm)

Medium + bacteria - S

Medium + bacteria + S

SUGGESTED CONCLUSSIONS



IRON-RICH MATERIAL

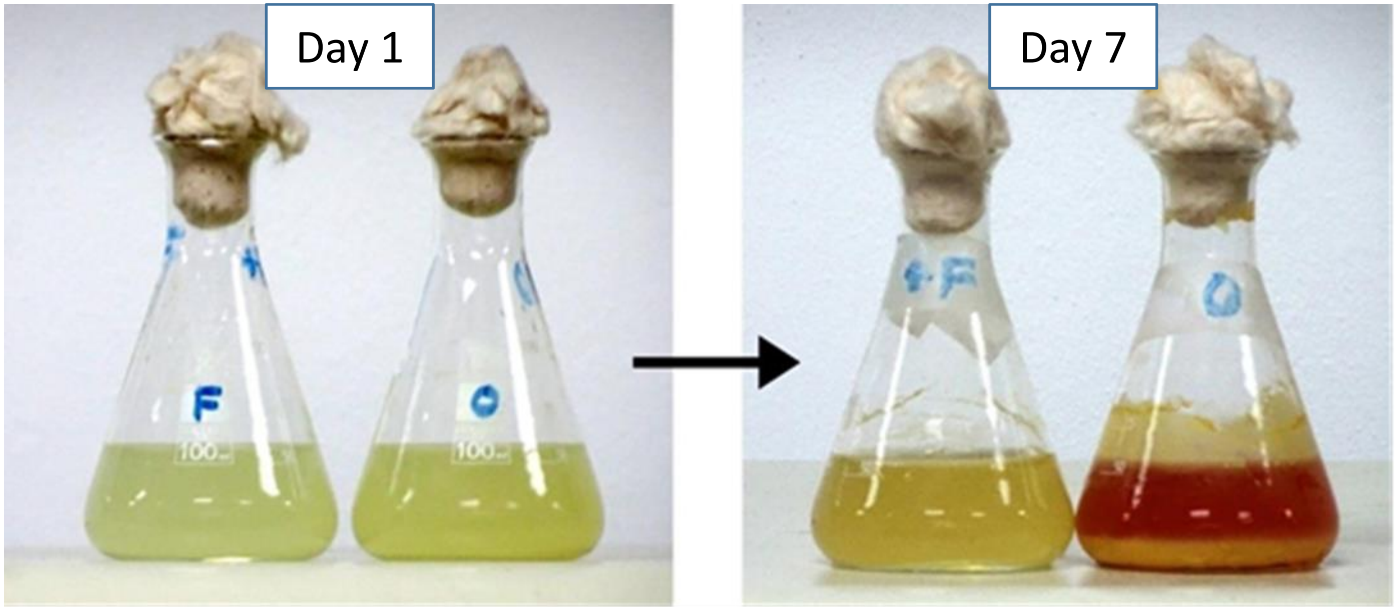
BIOMACHINING OF COPPER SLAGS

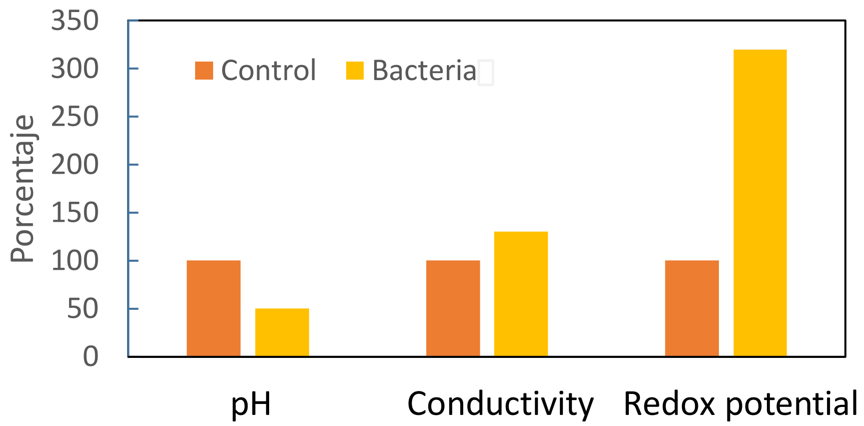
Components (%) ± SD	
Cu	1,30 ± 0.190
Fe	44,93 ± 0.870
Fe_3O_4	13,63 ± 1.790
SiO_2	29,58 ± 0.81
Al	1,68 ± 0.150
Ca	0,94 ± 0.130
K	0,48 ± 0.043
Mg	0,40 ± 0.053
Na	0,07 ± 0.026

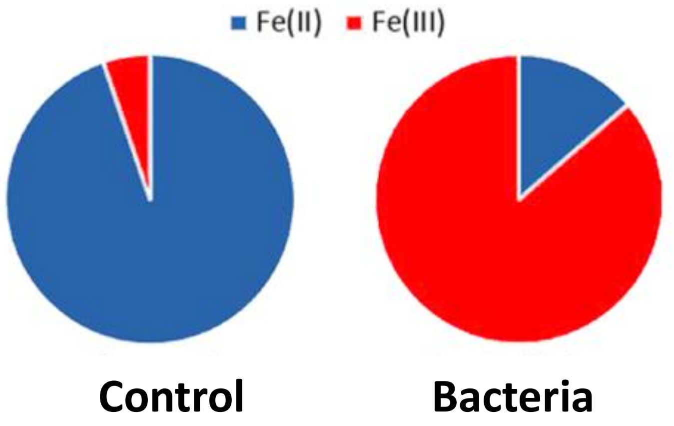
Biomachining: microbiologically controlled corrosion, is a process based on the elimination of a metallic material by solubilization following chemical reactions in the solution.

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

COPPER SLAGS AS SOURCE OF IRON FOR BACTERIA

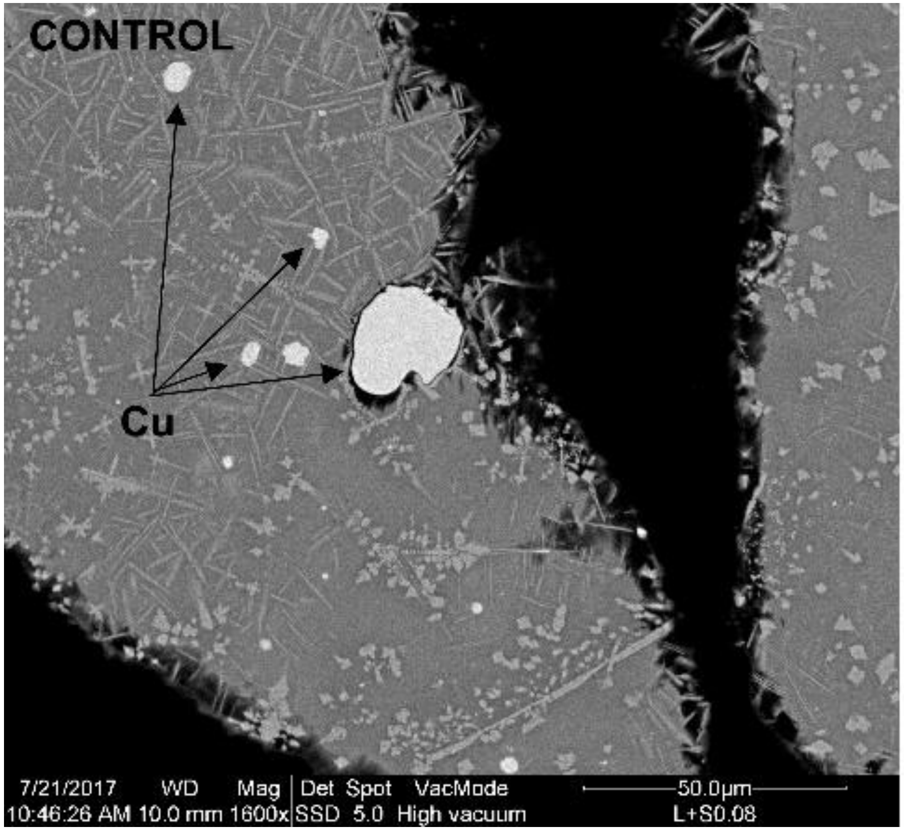


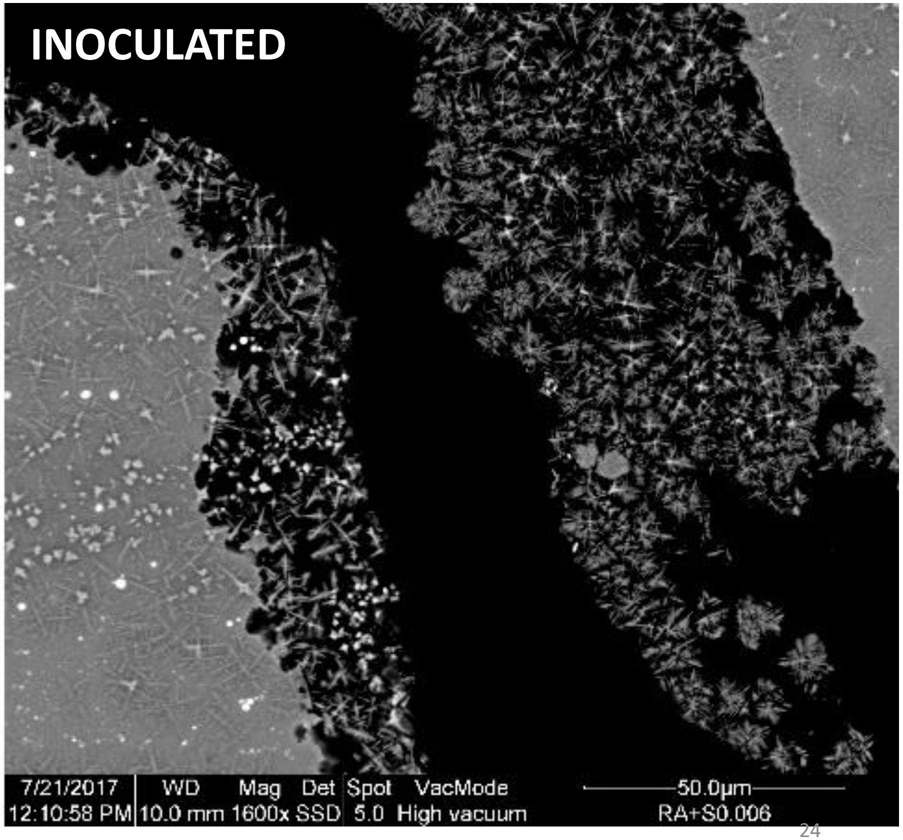




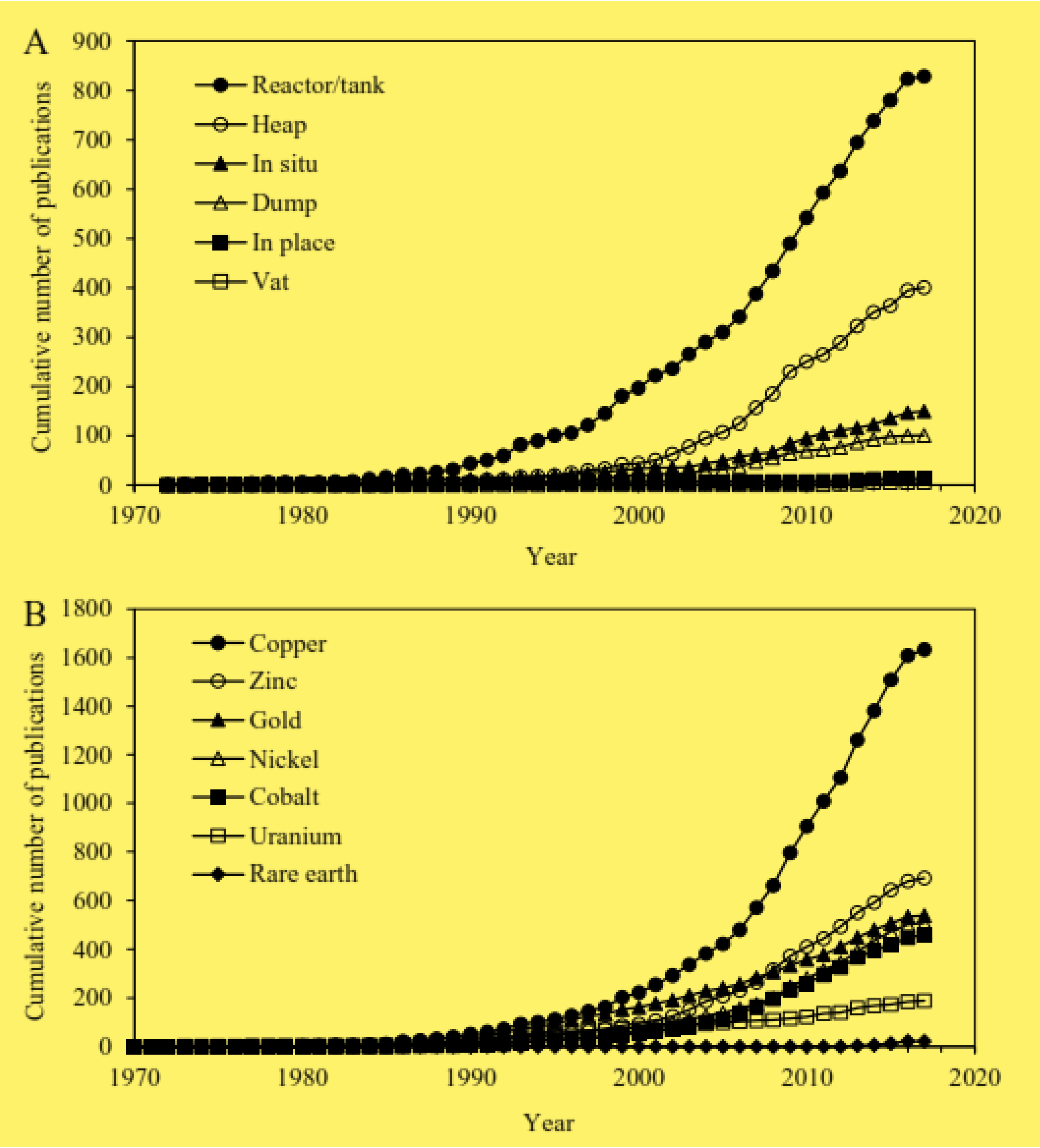
RESULTS: 14 DAYS OF INCUBATION

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)

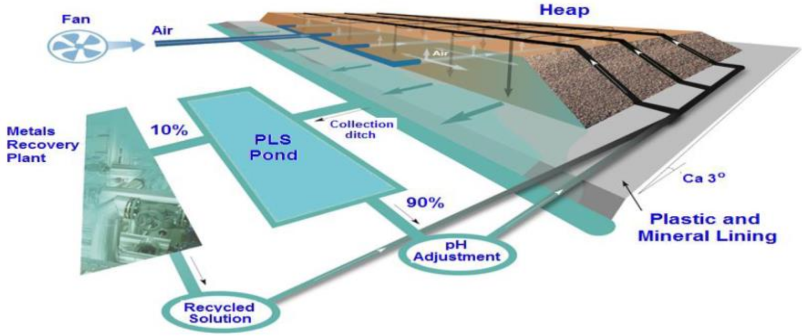


About 180000 papers from 1990.

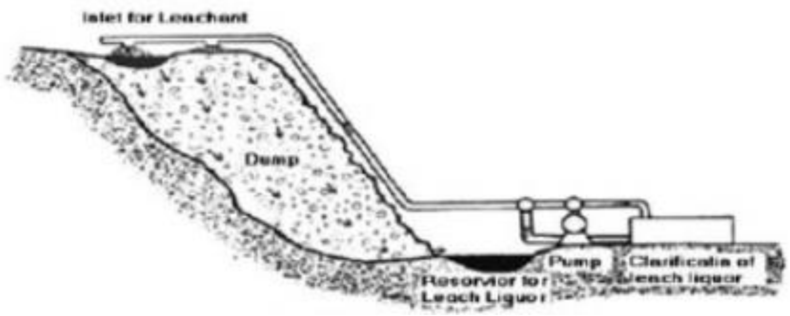
Kaksonen et al., 2017; Kucuker & Kutcha, 2018

BIOMINING: COMMON STRATEGIES

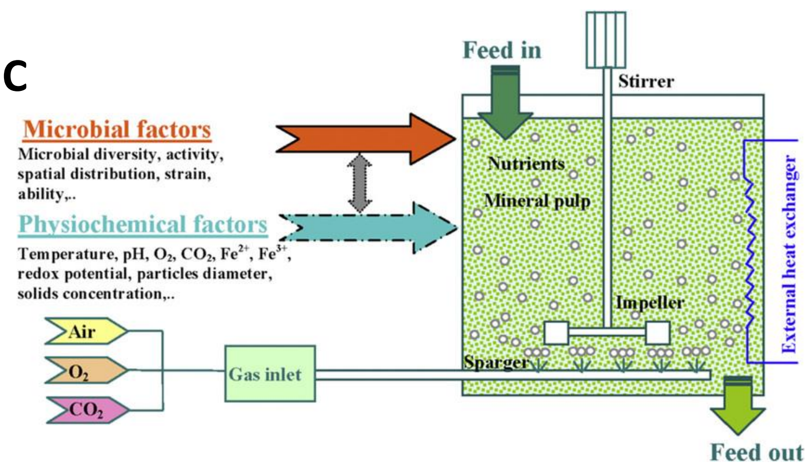
A



B



C



(Based on http://www.spaceship-earth.org/REM/Naeveke.htm y Mahmoud et al., 2017)

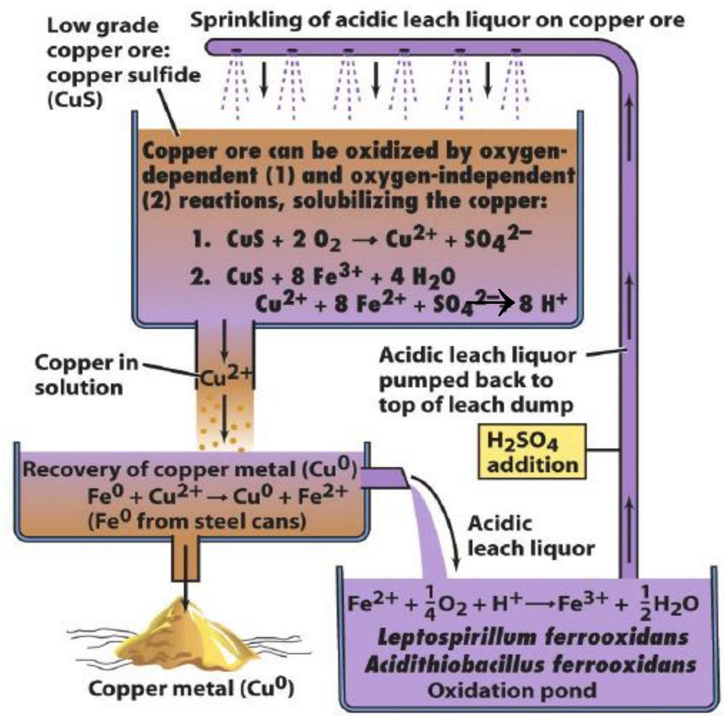
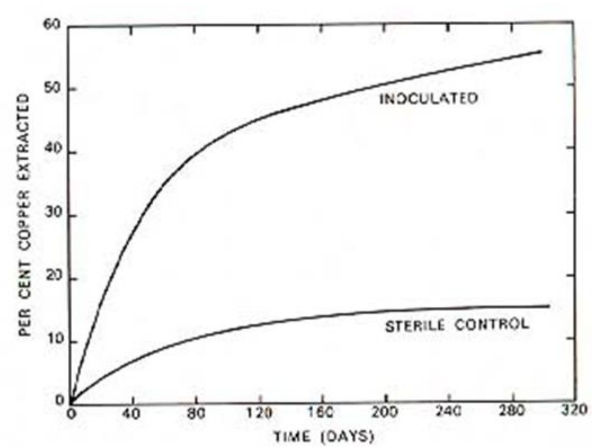


Figure 19-38 Brock Biology of Microorganisms 11/e



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

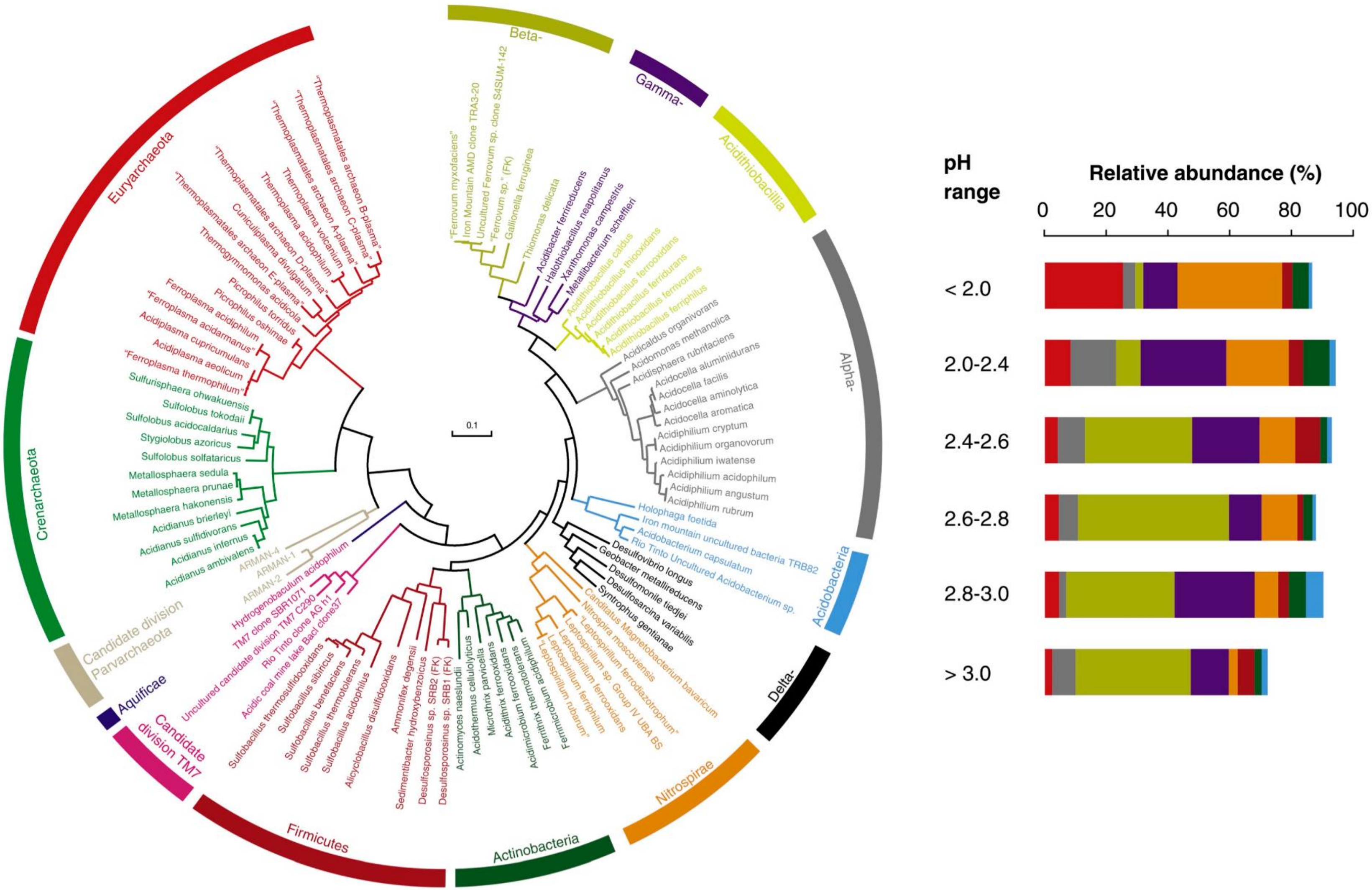
MISHRA EL AT., 2005

INDUSTRIAL PLANTS OF COPPER BIOLEACHING IN CHINA

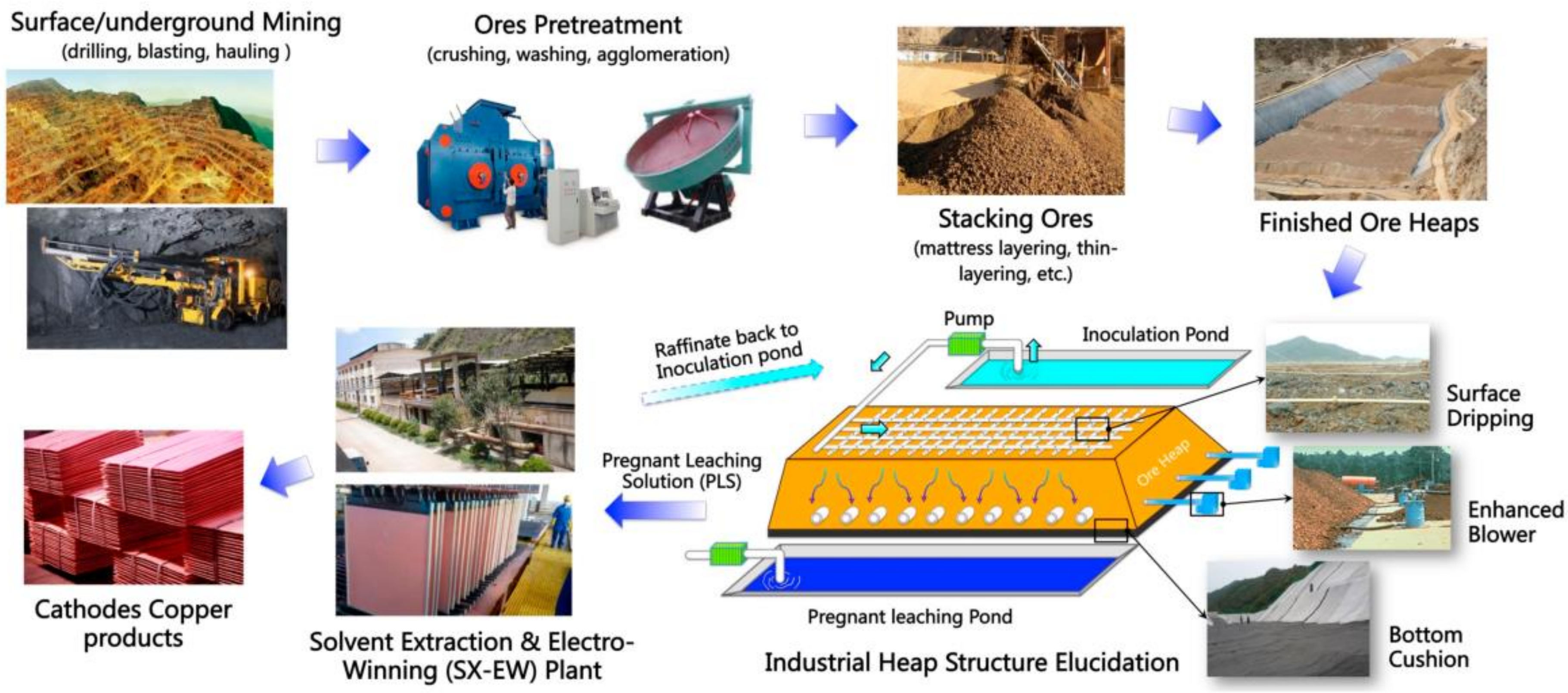
First mine: Dexing Copper Mine, 1997

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)

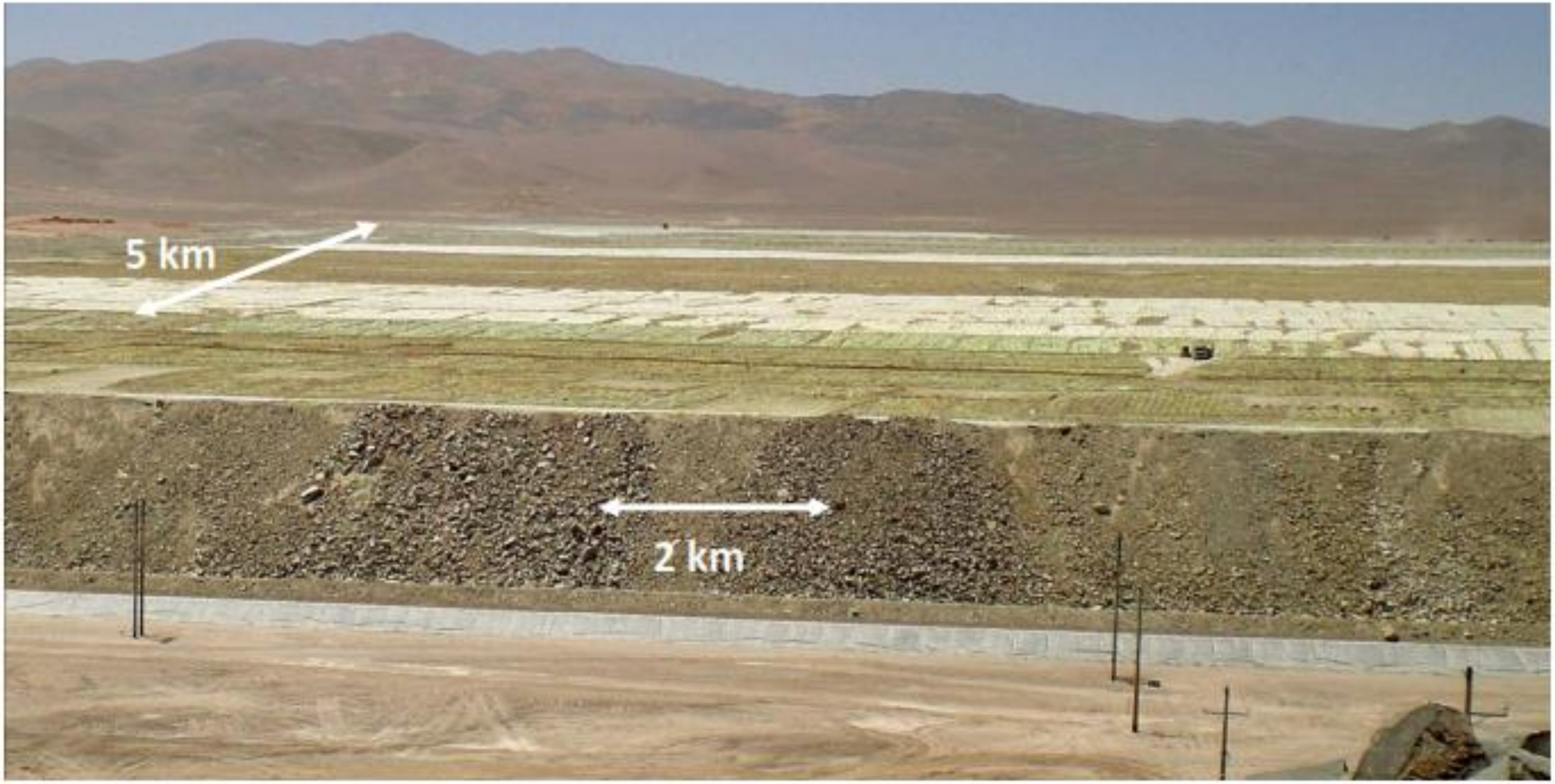
Heap

irrigation

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

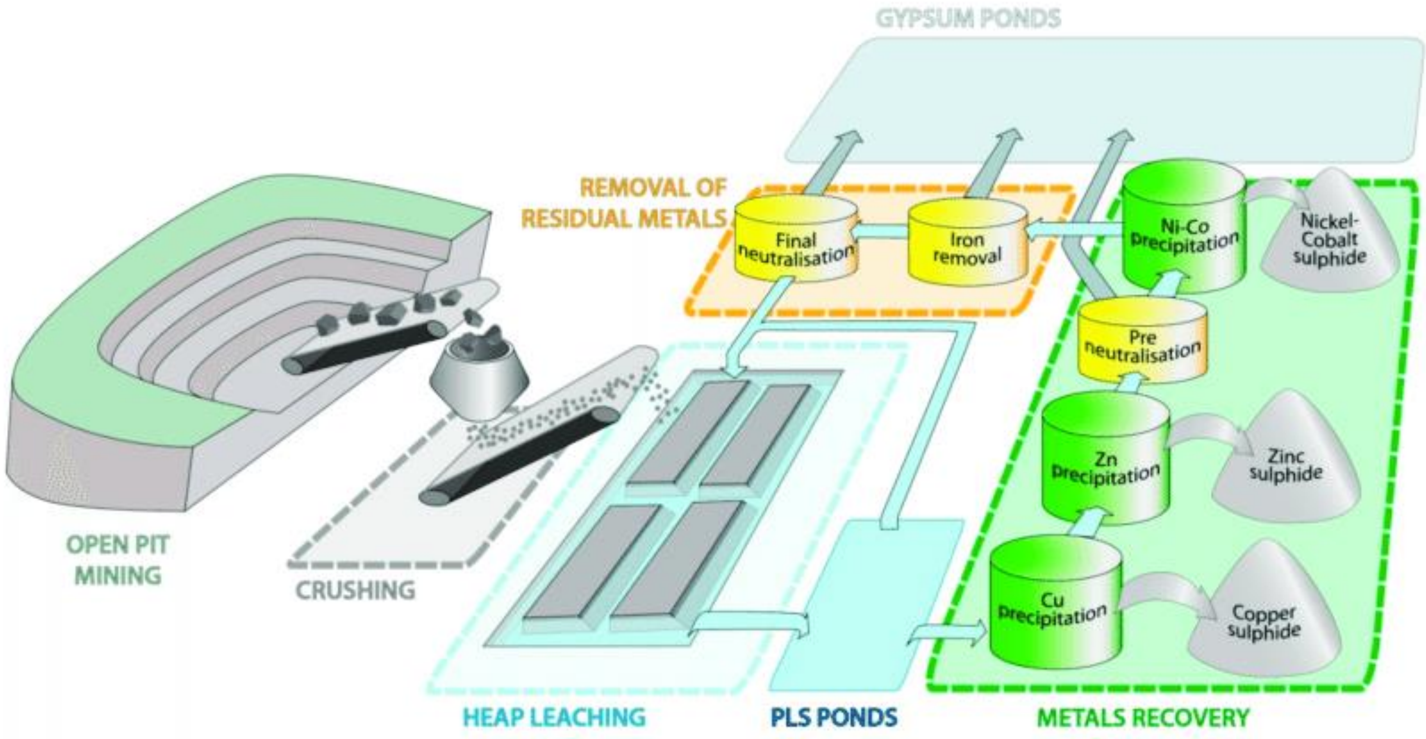
PLS stream

COPPER BIOHEAPLEACHING (CHILE)

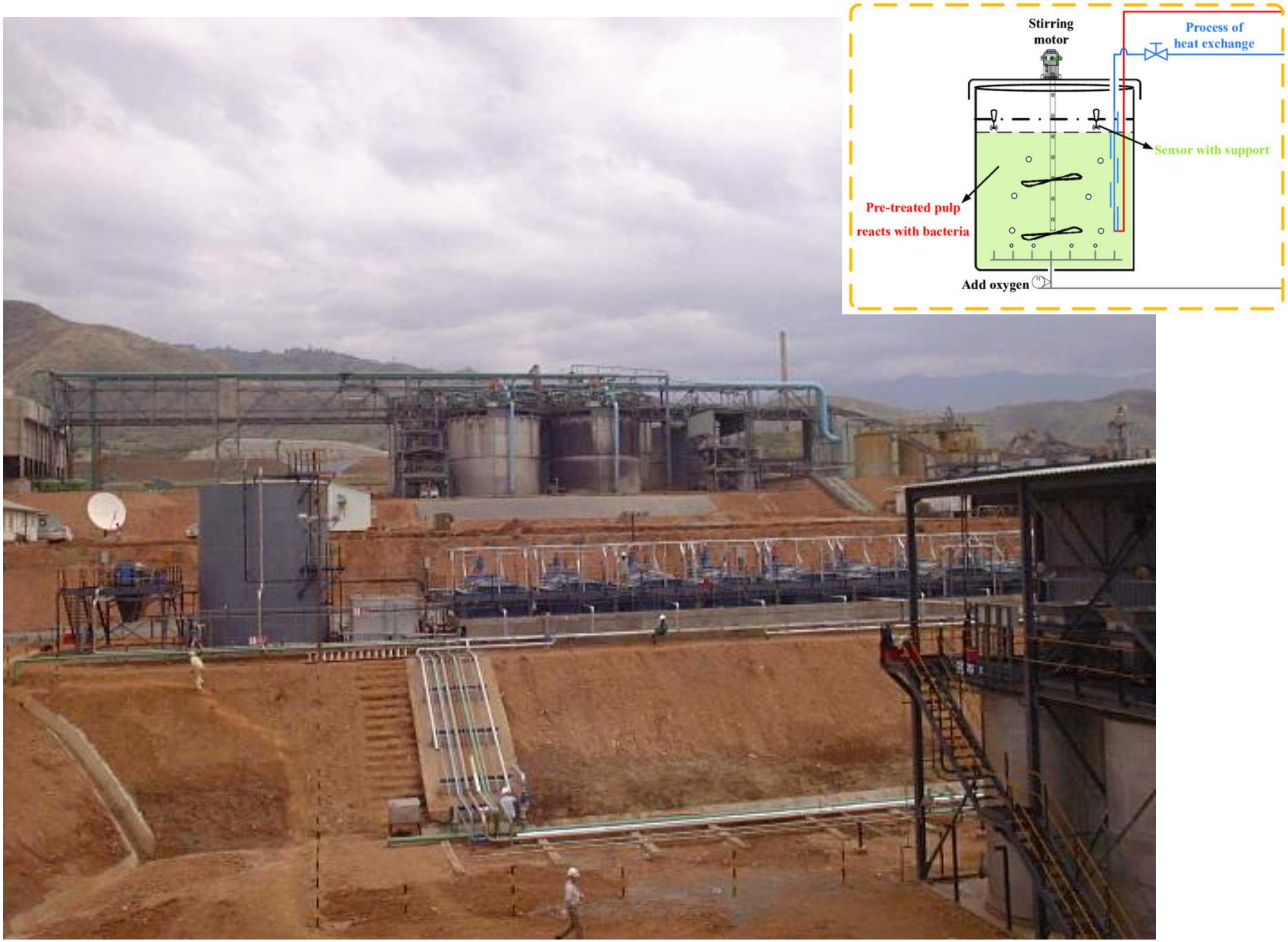


Escondida, copper mine, Chile

NICKEL BIOHEAPLEACHING (Talvivaara Sotkamo Mine, Finland)

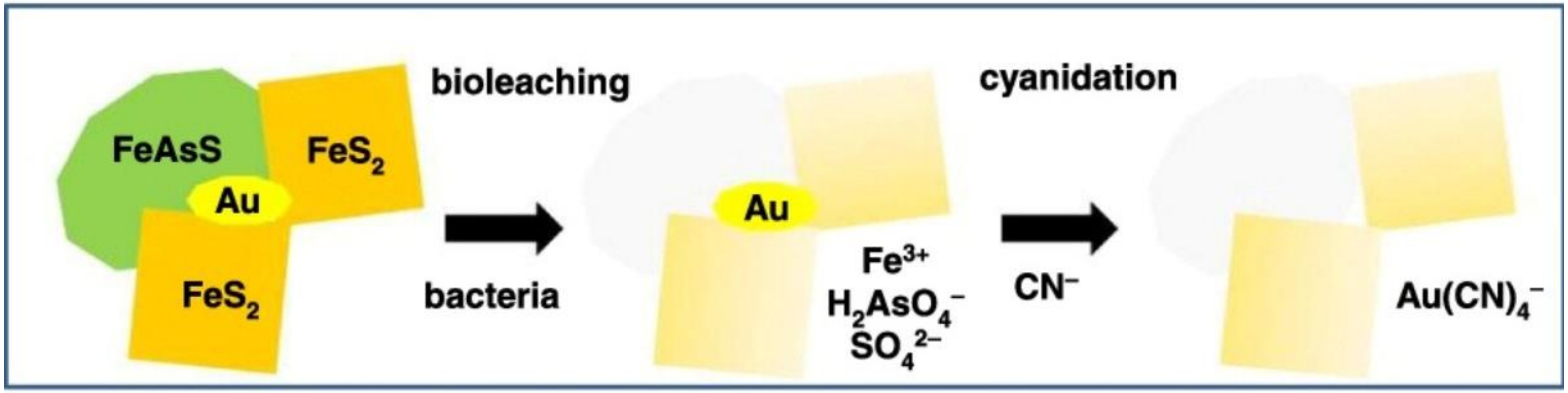


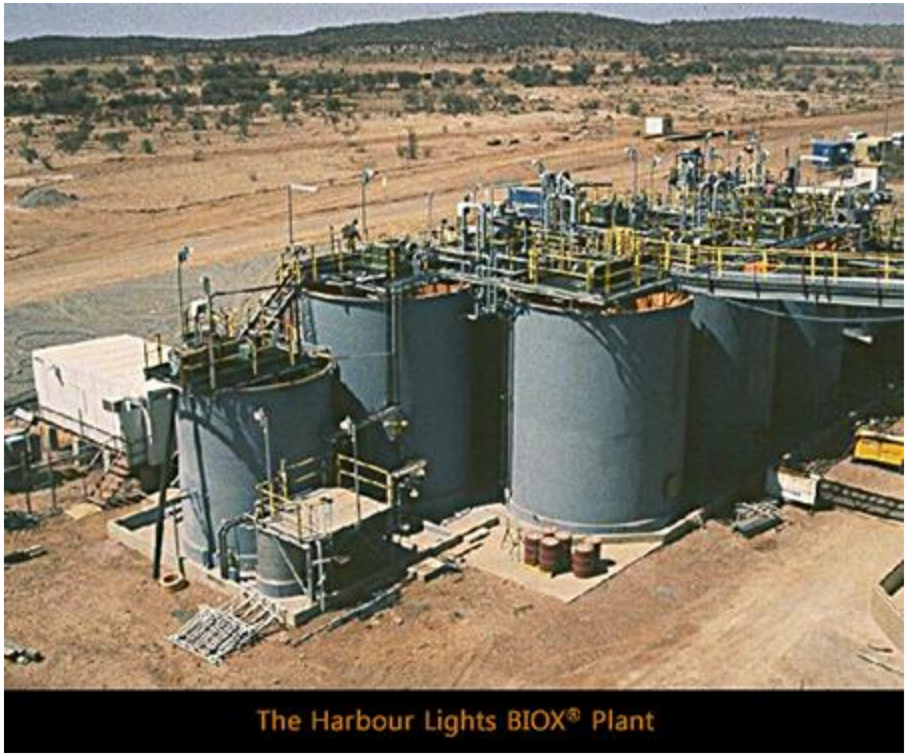
COPPER BIOLEACHING IN TANK



. Copper bioleaching industry in Uganda

REFRACTORY GOLD ORE BIOLEACHING



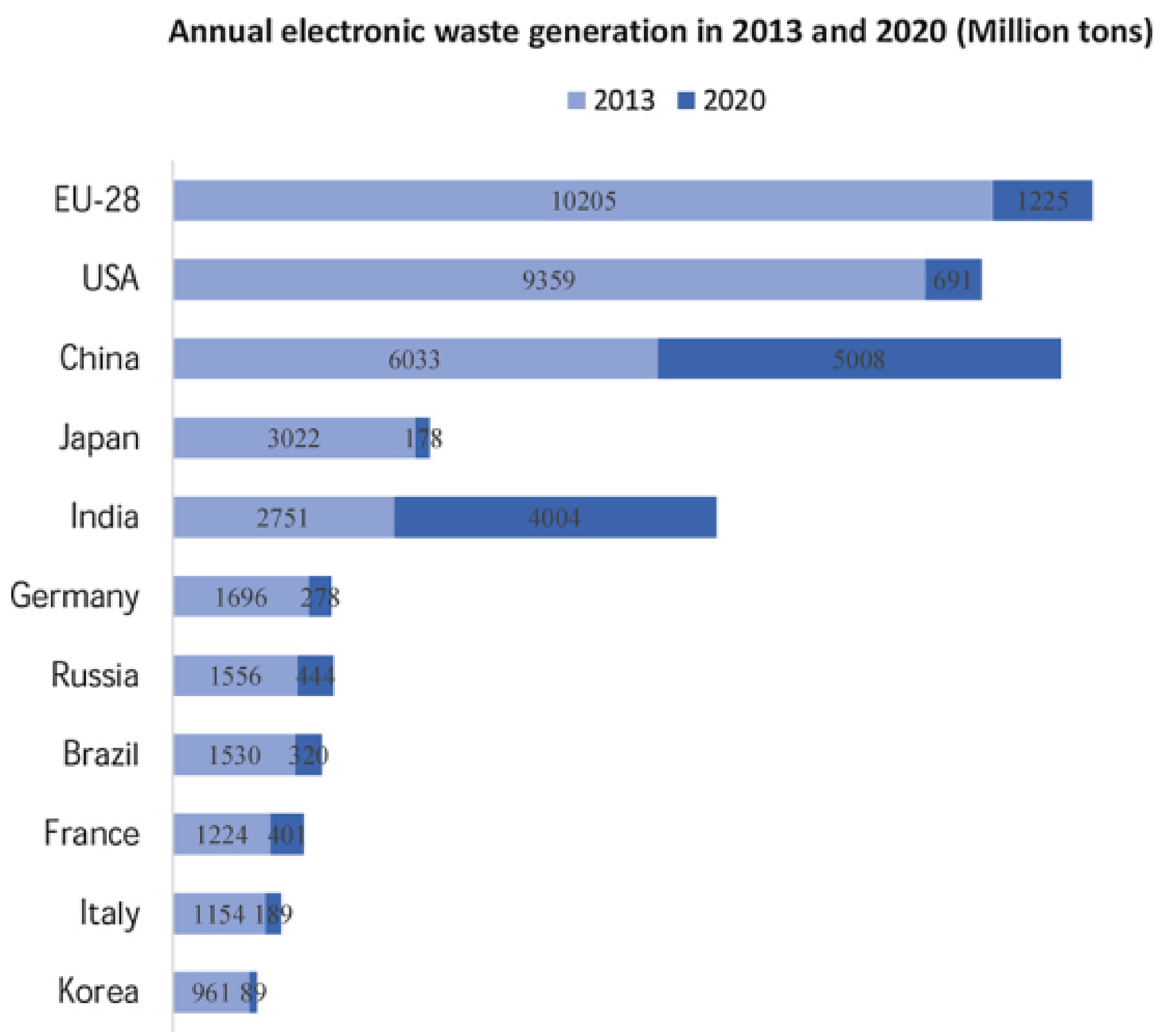


Australia

Ghana

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

METALS IN WASTE



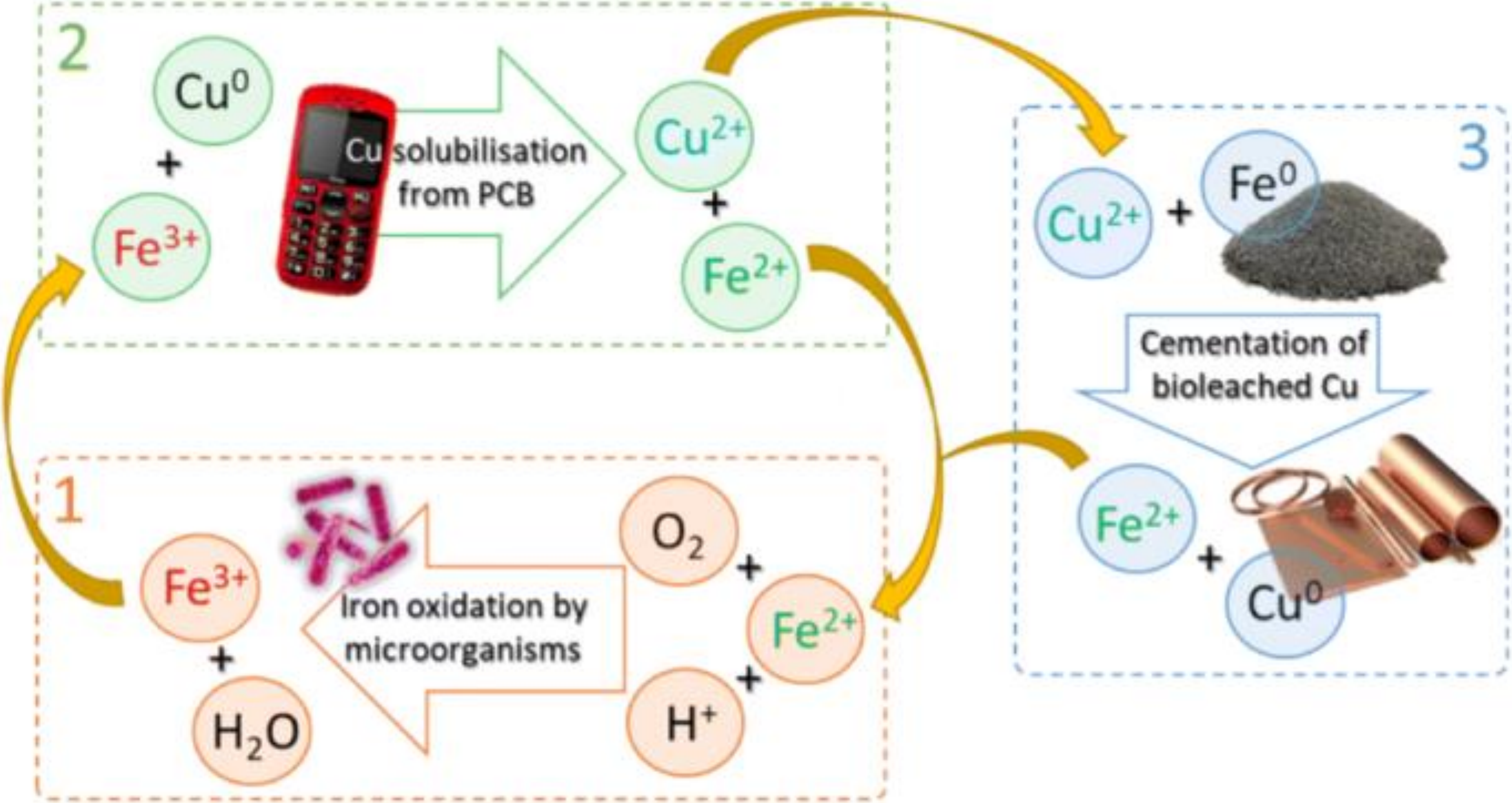
Işıldar et al., 2019

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* *Acidithiobacillus ferrooxidans* *Aspergillus niger*[1] *Penicillium simplicissimum*[1]
Electronic scrap	Al, Cu, Ni, Pb, Sn, Zn, Au	*Acidithiobacillus ferrooxidans* *Acidithiobacillus thiooxidans* *Aspergillus niger*[1] *Penicillium simplicissimum*[1] *Cromobacterium violaceum*[2] *Sulfobacillus thermosulfidooxidans*[3]
Municipal solid waste Fly ash	Al, Fe, Mn, Ni, Cd, Cr, Cu, Ni, Pb, Zn	*Acidithiobacillus thiooxidans* *Acidithiobacillus ferrooxidans* *Pseudomonas putida*[4] *Bacillus megaterium*[5] *Aspergillus niger*[1] *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], *Pseudomonas fluorescens*[4]

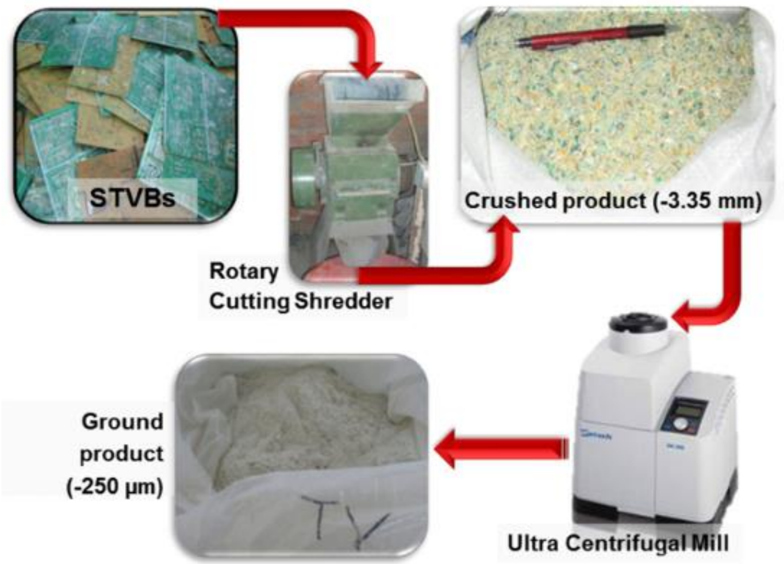
Bharadwaj y Ting, 2011; Kucuker y Kuchta, 2018

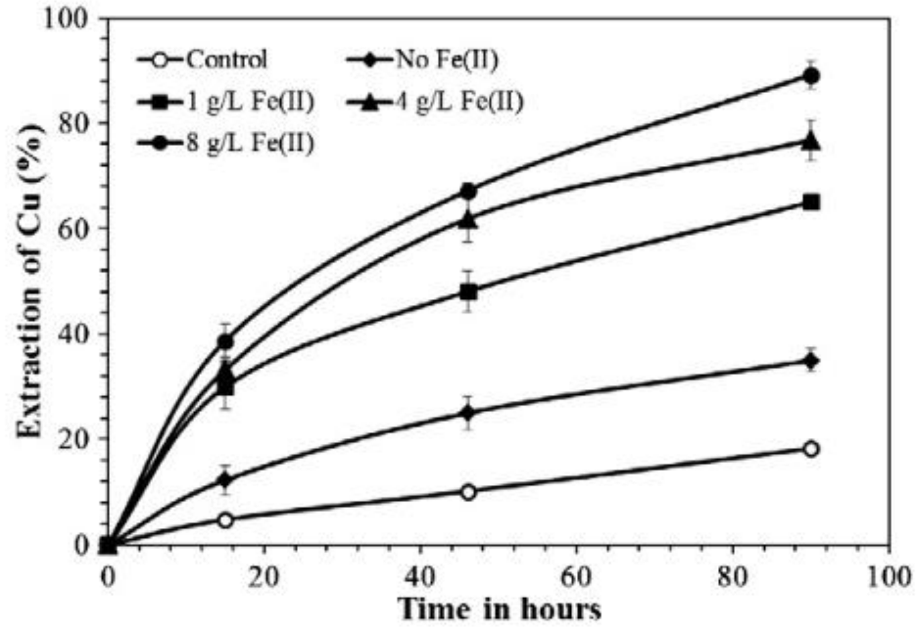
COPPER RECOVERY FROM E-WASTES



Benzal et al., 2020

EXAMPLE: COPPER BIOLEACHING USING TV WASTE



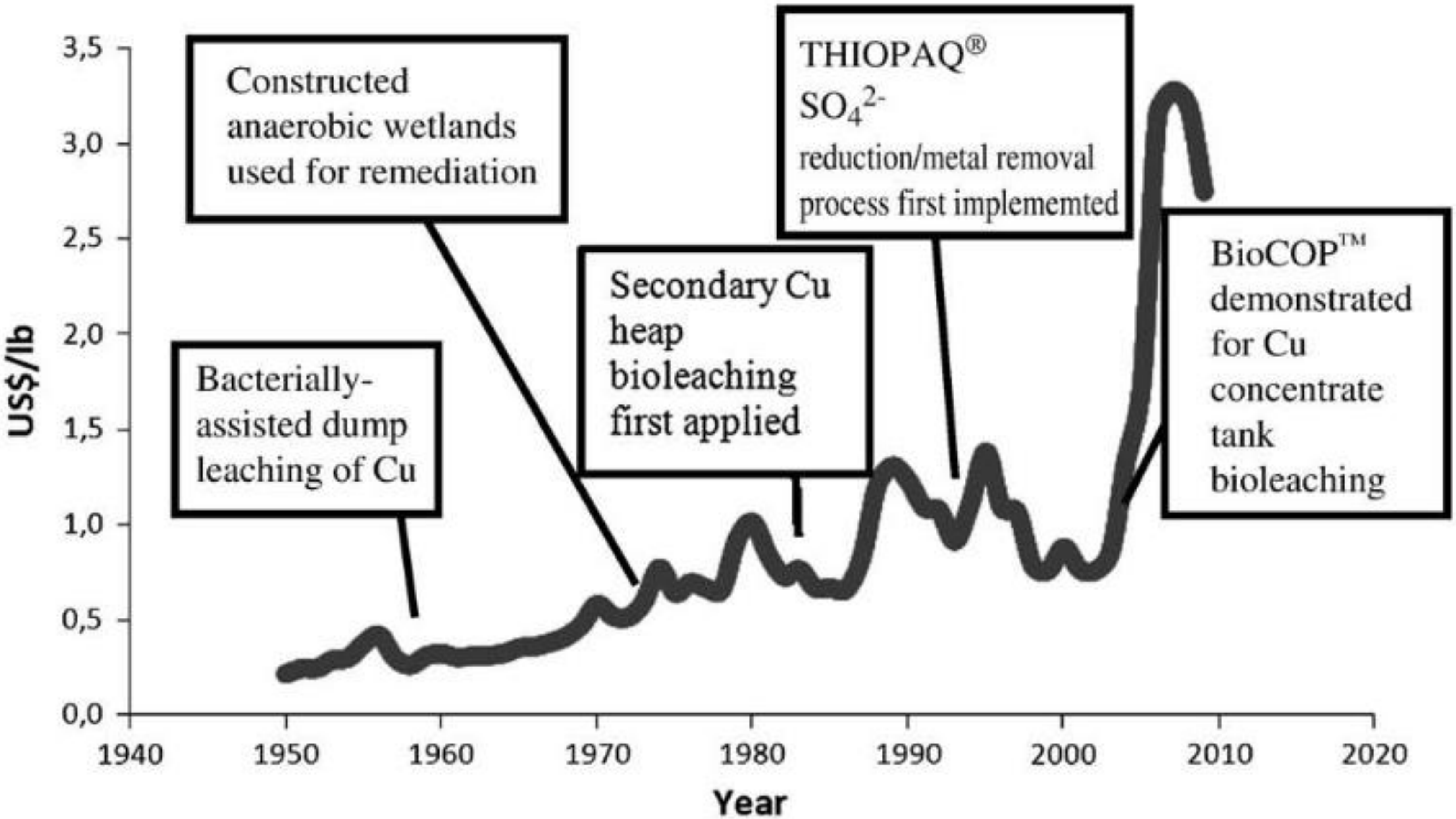


$$2Fe^{2+} + {}^{1}/_{2}\,O_2 + H^{+} \xrightarrow{\text{bacteria}} 2Fe^{3+} + H_2O$$

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

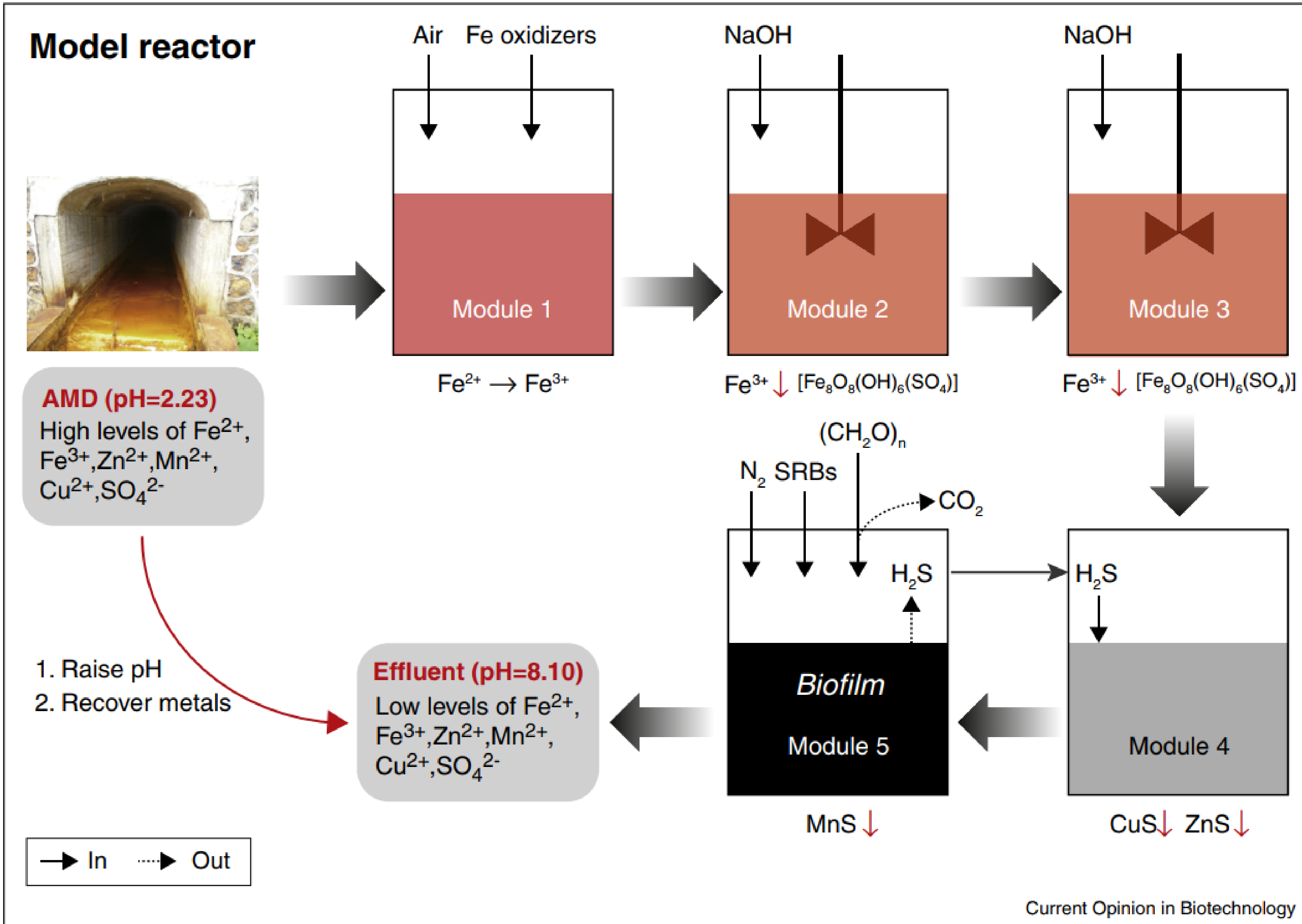
Bas et al., 2013

BIOMETALLURGY AS AN ALTERNATIVE

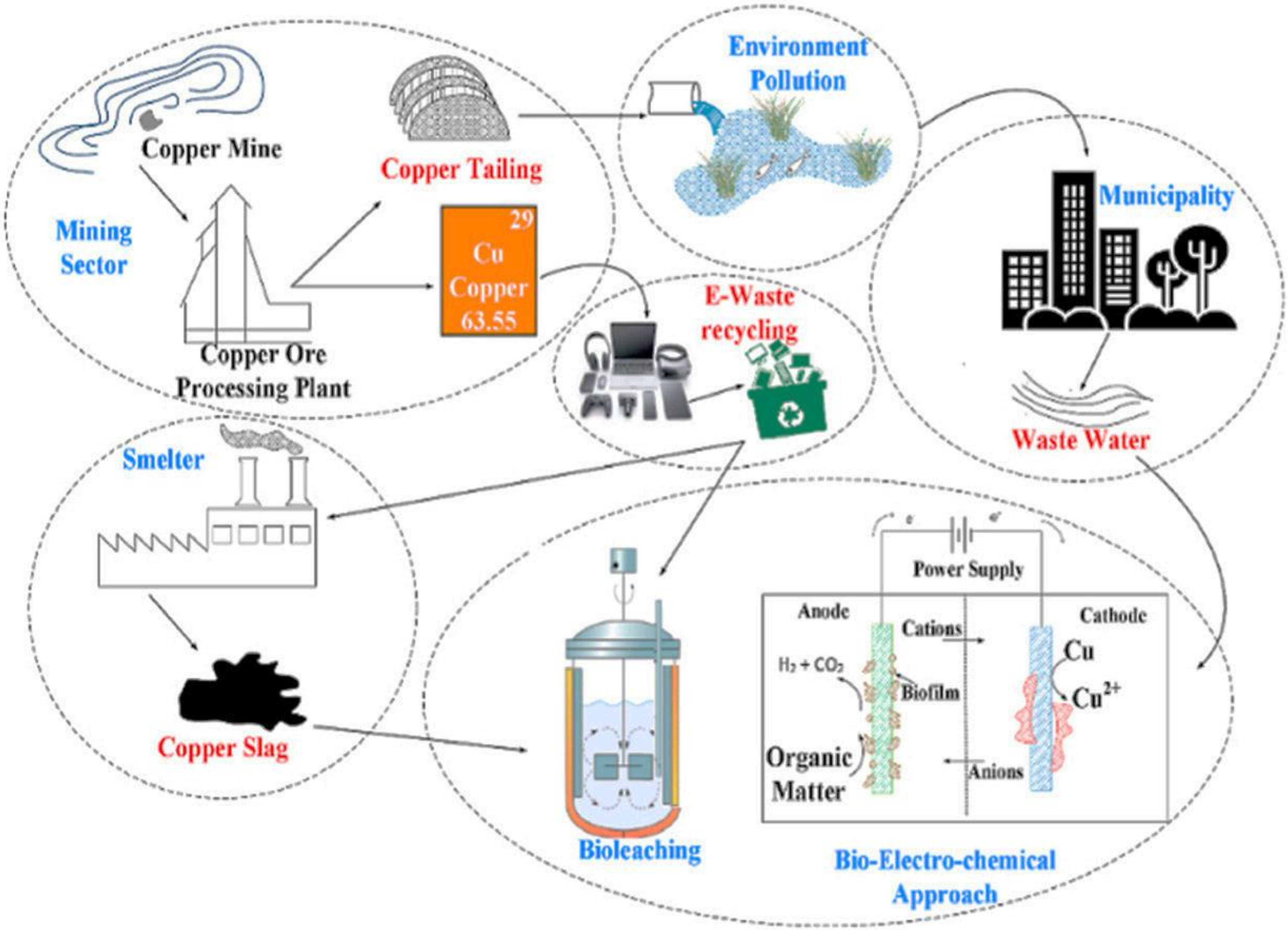


Batty y Rorke, 2006

BIOREMEDIATION OF POLLUTED SOILS AND WATERS



INTEGRATED BIOLEACHING-ELECTROMETALLURGY FOR COPPER RECOVERY



Brar et al (2021). Journal of Cleaner Production. https://doi.org/10.1016/j.jclepro.2020.125257

SELECTED REFERENCES

- Brar KK et al. (2021). Integrated bioleaching-electrometallurgy for copper recovery - A critical review. DOI: 10.1016/j.jclepro.2020.125257
- Chen L-x (2016). Microbial communities, processes and functions in acid mine drainage ecosystems. DOI: 10.1016/j.copbio.2016.01.013
- Falagán C, Grail BM, Johnson DB (2016). New approaches for extracting and recovering metals from mine tailings. DOI: 10.1016/j.mineng.2016.10.008
- Işıldar A et al. (2019).Biotechnological strategies for the recovery of valuable and critical raw materials from waste electrical and electronic equipment (WEEE) – A review. DOI. 10.1016/j.jhazmat.2018.08.050
- Jorjani E & Sabzkoohi HA (2022). Gold leaching from ores using biogenic lixiviants – A review. DOI: 10.1016/j.crbiot.2021.12.003
- Kucuker MA & and Kuchta K (2018). Biomining – biotechnological systems for the extraction and recovery of metals from secondary sources. DOI: 10.30955/gnj.002692
- Lee J-C & Pandey BD (2011). Bio-processing of solid wastes and secondary resources for metal extraction - A review. DOI: 10.1016/j.wasman.2011.08.010
- Ma L et al. (2016). Bioleaching of the mixed oxide-sulfide copper ore by artificial indigenous and exogenous microbial community. DOI: 10.1016/j.hydromet.2016.12.007
- Tornos F, López-Pamo E, Sánchez-España, FJ (2008). The Iberian Pyritic Belt. In: Contextos geológicos españoles: una aproximación al patrimonio geológico de relevancia internacional. Chapter 4. Publisher: Instituto Geológico y Minero de España, Madrid.
- Yin et al. (2018) Copper Bioleaching in China: Review and Prospect. DOI: 10.3390/min8020032


Thanks for your attention