JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

Bridging Laboratory and Field Performance in Copper Sulfide Bio-Heap Leaching: Critical Evaluation of Bottle-Roll, Column, and Pilot Testing

Antonio Clareti Pereira, PhD
PhD in Chemical Engineering
University of São Paulo (USP)
Belo Horizonte, Minas Gerais, Brazil
E-mail: claretipereira@gmail.com
ORCID: https://orcid.org/0000-0001-8115-4279

Abstract

Laboratory extraction profiles from copper sulfide bioleaching are frequently treated as predictors of heap performance. However, the experimental regimes differ in wetting, gas access, thermal inertia, microbial attachment, and mineralogical heterogeneity. This critical review evaluates the transferability of evidence across bottle-roll or stirred tests, packed columns, large columns, pilot heaps, and commercial operations. The synthesis integrates the supplied bibliography, explicitly distinguishing copper-specific evidence, mechanistic evidence from acidophilic systems, and transferable analogies from other leaching ores. Bottle tests are useful for preliminary reaction screening but cannot resolve preferential flow or gravity drainage; columns introduce coupled liquid–gas transport, whereas pilot heaps are needed to test the persistence of aeration, solution distribution, and thermal gradients under more representative boundary conditions. The proposed framework treats scale-up as preservation of coupled mechanisms, not replication of an isolated recovery percentage. A tiered evidence ladder, scale-fidelity matrix, and decision gates guide the design, reporting, and interpretation of industrially relevant test programs.

Keywords: Copper sulfides; Bioleaching; Heap leaching; Column testing; Pilot-scale testing; Scale-up

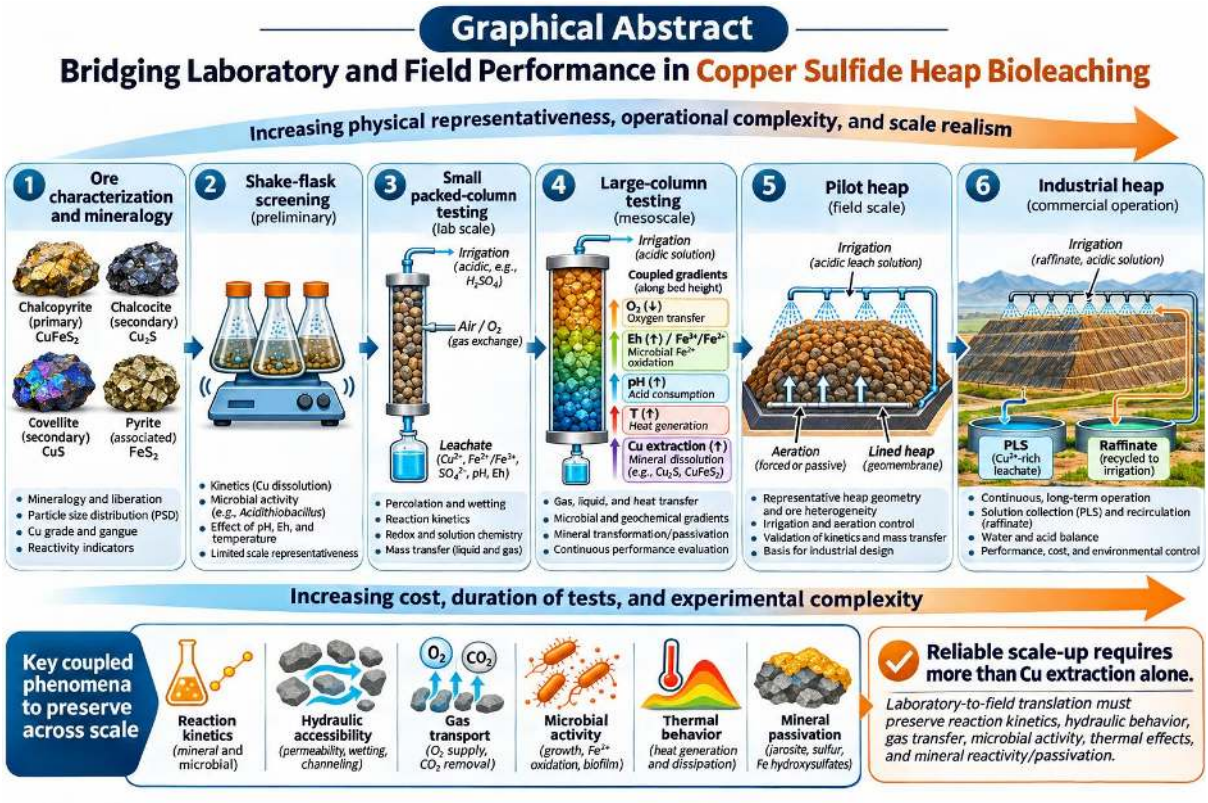
Highlights

- Bottle-roll testing screens reactivity but does not reproduce heap hydrodynamics.
- Column tests resolve percolation and gas-transfer limitations absent from slurry tests.
- Pilot heaps are needed for coupled heat, microbial, and hydraulic validation.
- Industrial scale-up requires evidence-based, uncertainty-aware go/no-go criteria.

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

Graphical Abstract



Graphical Abstract. Graphical abstract: experimental evidence ladder.
Note. Conceptual illustration prepared for this review with AI-assisted graphics; scientific content and labels require author verification before publication. No quantitative magnitude is implied.

1. Introduction

The central question is not whether a sulfide ore can dissolve in a laboratory reactor, but whether its controlling reactions remain accessible in an unsaturated, heterogeneous, aerated heap. Low copper grades and refractory mineral associations elevate the importance of test representativeness. Selective reporting of final recovery can obscure the effects of irrigation distribution, gas transfer, and temperature history. The review therefore distinguishes intrinsic chemical and biological potential from the transport-conditioned recovery actually attainable in a field lift.

The review is a structured critical synthesis of the 150-item user-supplied bibliography, encompassing articles published from 2010 through 2026. The source set was assembled using stage-specific search strings provided with the bibliography; this manuscript

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

does not claim to have conducted a new independent database search, formal PRISMA screening, or article-by-article full-text verification. Studies are treated according to whether they provide copper-specific heap observations, general acidophile mechanisms, or transfer insights from other minerals.

Industrial relevance should be established by distinguishing chemical extraction potential from accessible ore volume. A favorable flask response provides no direct measurement of the fraction of a heap reached by irrigation and oxygen. The literature assembled here spans industrial case histories, biological fundamentals, and copper-extraction technologies; these are related lines of evidence rather than interchangeable demonstrations of successful scale-up. (Abid et al., 2026; Bellenberg et al., 2012; Bevilaqua et al., 2013). These sources frame the relevant mechanism or experimental question; their individual quantitative findings have not been independently verified.

Commercial application also entails constraints absent from ideal laboratory controls: variable feed mineralogy, residence-time distributions, and site-specific water management. Therefore, comparisons across projects need more than an endpoint copper-recovery percentage; they require documented material balances, operating history, and the scale at which performance was measured. (Bosecker, 2014; Brar et al., 2021; Bryan et al., 2012).

Acidophile ecology and surface chemistry offer mechanisms, but evidence from isolated cultures or other feedstocks cannot establish the rate-controlling process within a copper sulfide heap. Microbial capability must be separated from oxygen delivery, ferric-ion regeneration, and active mineral surface area. (Castro et al., 2015; Corbett et al., 2017; Dong et al., 2022).

This synthesis examines what each experimental level can credibly establish, which phenomena remain unobserved, and what minimum evidence should support escalation to the next level. The proposed decision gates are engineering recommendations, not universally validated numerical thresholds. (Falagán et al., 2017; González et al., 2020; Hedrich et al., 2018).

Industrial relevance should be established by distinguishing chemical extraction potential from accessible ore volume. A favorable flask response provides no direct

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

measurement of the fraction of a heap reached by irrigation and oxygen. The literature assembled here spans industrial case histories, biological fundamentals, and copper-extraction technologies; these are related lines of evidence rather than interchangeable demonstrations of successful scale-up. (Johnson, 2014; Johnson, 2015; Johnson, 2018). These sources frame the relevant mechanism or experimental question; their individual quantitative findings have not been independently verified.

Commercial application also entails constraints absent from ideal laboratory controls: variable feed mineralogy, residence-time distributions, and site-specific water management. Therefore, comparisons across projects need more than an endpoint copper-recovery percentage; they require documented material balances, operating history, and the scale at which performance was measured. (Kaksonen et al., 2020; Lorenzo-Tallafigo et al., 2022; Mäkinen et al., 2021).

Acidophile ecology and surface chemistry offer mechanisms, but evidence from isolated cultures or other feedstocks cannot establish the rate-controlling process within a copper sulfide heap. Microbial capability must be separated from oxygen delivery, ferric-ion regeneration, and active mineral surface area. (Martins et al., 2023; Noguchi et al., 2020; Orell et al., 2012).

This synthesis examines what each experimental level can credibly establish, which phenomena remain unobserved, and what minimum evidence should support escalation to the next level. The proposed decision gates are engineering recommendations, not universally validated numerical thresholds. (Pakostova et al., 2018; Richter et al., 2018; Santos et al., 2020).

Industrial relevance should be established by distinguishing chemical extraction potential from accessible ore volume. A favorable flask response provides no direct measurement of the fraction of a heap reached by irrigation and oxygen. The literature assembled here spans industrial case histories, biological fundamentals, and copper-extraction technologies; these are related lines of evidence rather than interchangeable demonstrations of successful scale-up. (Seredkin et al., 2016; Srichandan et al., 2019; Toro et

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

al., 2021). These sources frame the relevant mechanism or experimental question; their individual quantitative findings have not been independently verified.

Commercial application also entails constraints absent from ideal laboratory controls: variable feed mineralogy, residence-time distributions, and site-specific water management. Therefore, comparisons across projects need more than an endpoint copper-recovery percentage; they require documented material balances, operating history, and the scale at which performance was measured. (Vakylabad et al., 2022; Velásquez-Yévenes et al., 2022; Watling, 2014).

Acidophile ecology and surface chemistry offer mechanisms, but evidence from isolated cultures or other feedstocks cannot establish the rate-controlling process within a copper sulfide heap. Microbial capability must be separated from oxygen delivery, ferric-ion regeneration, and active mineral surface area. (Whitworth et al., 2022; Zhang et al., 2020).

2. Fundamentals of Copper Sulfide Bio-Heap Leaching

Chalcopyrite, chalcocite, covellite, bornite, enargite, tennantite, and associated pyrite have distinct oxidation pathways and liberation requirements. Ferric oxidation of mineral sulfides is coupled to ferrous regeneration, sulfur oxidation, acid demand, secondary precipitation, and microbial energy metabolism. Surface passivation and mineral galvanic contacts may alter apparent kinetics. A viable community is necessary but insufficient unless ferric regeneration, oxygen delivery, carbon supply, and solution connectivity remain sustained through the ore bed.

Figure 1 depicts the coupled controls of sulfide bioleaching. The arrows emphasize that microbial catalysis acts within physicochemical transport constraints; the figure is a conceptual synthesis rather than a calibrated mechanistic model.

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

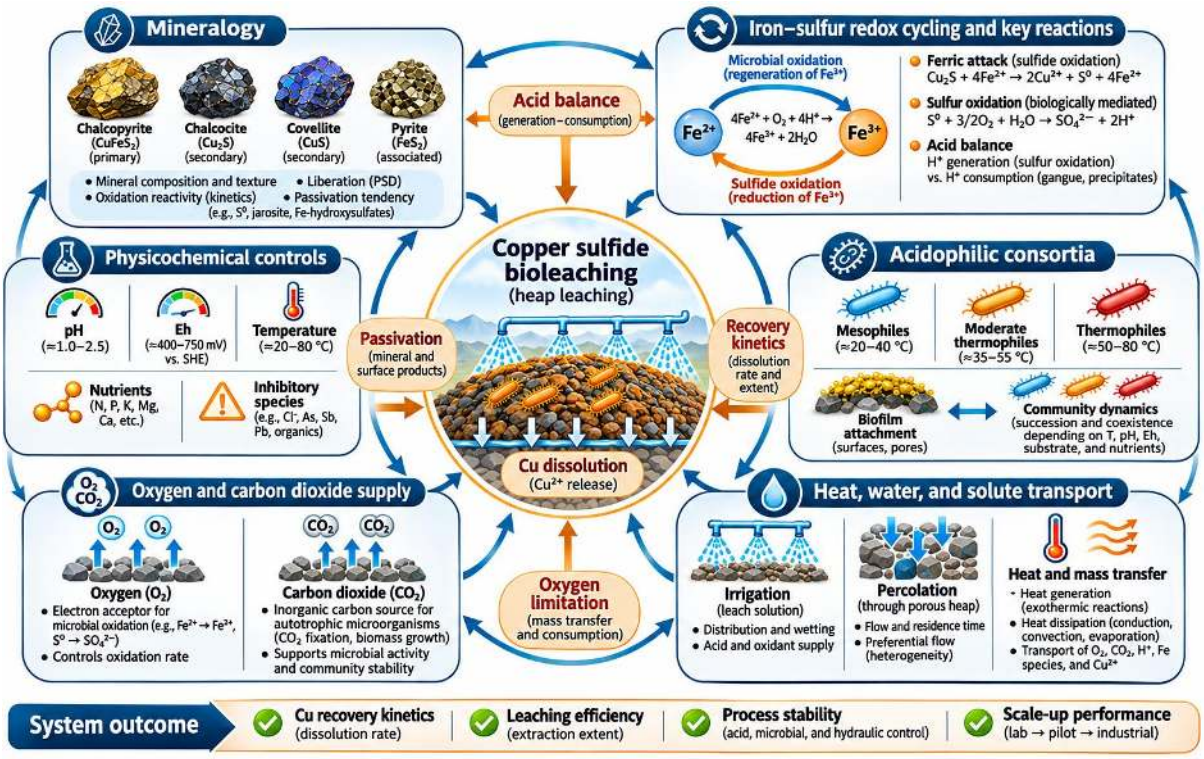


Figure 1. Multiphysics controls of copper sulfide bioleaching.

Note. Conceptual illustration prepared for this review with AI-assisted graphics; scientific content and labels require author verification before publication. No quantitative magnitude is implied.

Mineral-specific reactivity matters because secondary copper sulfides and chalcopyrite do not respond identically to the same oxidant potential. Pyrite may affect ferric cycling and heat release, whereas gangue minerals can consume acid and alter precipitation. Consequently, mineral identification without liberation and association data provides an incomplete explanation for bulk copper extraction. (Ahmadi et al., 2015; Bellenberg et al., 2015; Bellenberg et al., 2014). These sources frame the relevant mechanism or experimental question; their individual quantitative findings have not been independently verified.

Ferric attack and biological ferrous oxidation form a coupled cycle, but either component can become limiting. A reactor with active iron oxidizers may still underperform if transport restricts oxygen, while ferric-rich solution can cause localized precipitation or nonuniform reaction. Distinguishing chemical conversion from regeneration capacity is central to scale-up. (Bellenberg et al., 2021; Blake et al., 2012; Borilova et al., 2018).

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

Observations of biofilm attachment and redox metabolism explain how acidophiles interact with mineral surfaces; they do not directly measure the spatial coverage of an industrial bed. Colony counts, gene abundance, and iron-oxidation rates therefore answer different questions and must not be treated as equivalent measures of copper dissolution. (Buetti-Dinh et al., 2019; Castro et al., 2020; Díaz et al., 2020).

Temperature tolerance should likewise be linked to actual bed profiles, not simply to organism classification. Apparent passivation can reflect product-layer formation, solution chemistry, or transport obstruction, and a diagnostic experiment should attempt to separate these causes. (Dopson et al., 2012; Falagan et al., 2019; Harrison, 2016).

Mineral-specific reactivity matters because secondary copper sulfides and chalcopyrite do not respond identically to the same oxidant potential. Pyrite may affect ferric cycling and heat release, whereas gangue minerals can consume acid and alter precipitation. Consequently, mineral identification without liberation and association data provides an incomplete explanation for bulk copper extraction. (Hedrich et al., 2013; Issotta et al., 2018; Johnson et al., 2017). These sources frame the relevant mechanism or experimental question; their individual quantitative findings have not been independently verified.

Ferric attack and biological ferrous oxidation form a coupled cycle, but either component can become limiting. A reactor with active iron oxidizers may still underperform if transport restricts oxygen, while ferric-rich solution can cause localized precipitation or nonuniform reaction. Distinguishing chemical conversion from regeneration capacity is central to scale-up. (Johnson et al., 2020; Khaleque et al., 2020; Malik et al., 2022).

Observations of biofilm attachment and redox metabolism explain how acidophiles interact with mineral surfaces; they do not directly measure the spatial coverage of an industrial bed. Colony counts, gene abundance, and iron-oxidation rates therefore answer different questions and must not be treated as equivalent measures of copper dissolution. (Martinez-Bussenius et al., 2016; Moya-Beltrán et al., 2021; Norris et al., 2020).

Temperature tolerance should likewise be linked to actual bed profiles, not simply to organism classification. Apparent passivation can reflect product-layer formation, solution

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

chemistry, or transport obstruction, and a diagnostic experiment should attempt to separate these causes. (Peng et al., 2021; Quatrini et al., 2018; Ruiz et al., 2012).

Mineral-specific reactivity matters because secondary copper sulfides and chalcopyrite do not respond the same way to the same oxidant potential. Pyrite may affect ferric cycling and heat release, whereas gangue minerals can consume acid and alter precipitation. Consequently, mineral identification without liberation and association data provides an incomplete explanation for bulk copper extraction. (Shiers et al., 2017; Stanković et al., 2015; Tao et al., 2021). These sources frame the relevant mechanism or experimental question; their individual quantitative findings have not been independently verified.

Ferric attack and biological ferrous oxidation form a coupled cycle, but either component can become limiting. A reactor with active iron oxidizers may still underperform if transport restricts oxygen, while ferric-rich solution can cause localized precipitation or nonuniform reaction. Distinguishing chemical conversion from regeneration capacity is central to scale-up. (Vargas et al., 2020; Wang et al., 2022; Watling et al., 2016).

Observations of biofilm attachment and redox metabolism explain how acidophiles interact with mineral surfaces; they do not directly measure the spatial coverage of an industrial bed. Colony counts, gene abundance, and iron-oxidation rates therefore answer different questions and must not be treated as equivalent measures of copper dissolution. (Yin et al., 2018; Zhao et al., 2013).

3. Experimental Hierarchy and the Scale-Up Problem

Evidence must progress from tightly controlled, reaction-oriented assays to leach beds that are geometrically and operationally representative. Each step adds physical realism but also introduces heterogeneity and uncertainty. A column is not simply a larger bottle: it provides gravity-driven flow, imperfect wetting, gas displacement, and vertical gradients. Likewise, a large laboratory column may still lack the thermal inertia, lateral variability, and operational disruptions of a pilot heap.

The comparison in Table 1 highlights which observables are transferable and which require higher-scale verification.

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

Table 1. Experimental evidence and transfer limitations

Scale	Strength	Blind spot
Bottle/flask	Rapid chemical screening	No percolation or load
Small packed column	Gravity drainage and axial gradients	Wall and size effects
Large column	Greater depth and heterogeneity	Limited lateral field variation
Pilot heap	Field-like coupled behavior	High expense, finite duration
Industrial heap	Operational performance	Limited controlled replication

Note. This review provides a qualitative appraisal; ratings are methodological judgments, not experimentally measured recovery values.

Comparability requires a declared basis: ore source and mineralogy, particle-size distribution, geometry, irrigation and aeration, temperature, exposure time, and analytical uncertainty. Without that basis, apparent recovery agreement may conceal different transport constraints.

The decisive distinction between laboratory stages is not sample mass alone but whether boundary conditions preserve the controlling mechanism. Small columns reveal percolation yet can overstate the influence of walls and sample preparation. Pilot heaps add lateral heterogeneity and environmental variability, although even a successful pilot may not capture long-term commercial compaction. (Arpalahti et al., 2020; Bostelmann et al., 2020; Huang et al., 2025). These sources frame the relevant mechanism or experimental question; their individual quantitative findings have not been independently verified.

The decisive distinction between laboratory stages is not sample mass alone but whether boundary conditions preserve the controlling mechanism. Small columns reveal percolation yet can overstate the influence of walls and sample preparation. Pilot heaps add lateral heterogeneity and environmental variability, although even a successful pilot may not capture long-term commercial compaction. (Jia et al., 2021; Pereira, 2026c; Wang et al., 2024).

4. Bottle-Roll and Agitated Laboratory Testing

Bottle-roll, flask, and stirred-tank trials can compare ore blends, acid dosage, inoculation, ferric supply, redox response, and temperature sensitivity. Their benefit is controllability, not heap representativeness. Small particles, high liquid-to-solid ratios, mechanical suspension, and abundant aeration can accelerate extraction while suppressing

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

mechanisms that will dominate in heaps. Consequently, the slope of a bottle extraction curve cannot be interpreted as a field-scale kinetic constant without independent transport validation.

The comparison in Table 2 highlights which observables are transferable and which require higher-scale verification.

Table 2. Bottle-roll measurements and scale validity

Measure	Interpretation	Transfer qualification
Copper extraction	Potential reactivity	Not a field recovery forecast
Acid consumption	Chemical demand	Recheck under percolation
Redox response	Solution oxidizing capacity	Check distributed Fe regeneration
Microbial response	Slurry physiological potential	Verify surface colonization

Note. This review offers a qualitative appraisal; ratings are methodological judgments, not experimentally measured recovery values.

Comparability requires a declared basis: ore source and mineralogy, particle-size distribution, geometry, irrigation and aeration, temperature, exposure time, and analytical uncertainty. Without that basis, apparent recovery agreement may conceal different transport constraints.

The strongest defensible use of bottle-roll results is screening: ranking ore responses under controlled chemistry, measuring provisional acid consumption, and identifying inhibitory combinations. Mechanical agitation changes particle exposure and gas transfer, so you cannot directly assign an observed rate to a gravity-drained heap. A valid interpretation should report particle size, liquid-to-solid ratio, oxygen supply, temperature, inoculation, and sampling uncertainty. (Altinkaya et al., 2018; Bryan et al., 2011; Marín et al., 2021). These sources frame the relevant mechanism or experimental question; their individual quantitative findings have not been independently verified.

The strongest defensible use of bottle-roll results is screening: ranking ore responses under controlled chemistry, measuring provisional acid consumption, and identifying inhibitory combinations. Mechanical agitation changes particle exposure and gas transfer, so an observed rate cannot be directly assigned to a gravity-drained heap. A valid interpretation should report particle size, liquid-to-solid ratio, oxygen supply, temperature, inoculation, and sampling uncertainty. (Pereira, 2026b; Petersen, 2010; Shamsi et al., 2023).

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

The strongest defensible use of bottle-roll results is screening: ranking ore responses under controlled chemistry, measuring provisional acid consumption, and identifying inhibitory combinations. Mechanical agitation changes particle exposure and gas transfer, so you cannot directly assign an observed rate to a gravity-drained heap. A valid interpretation should report particle size, liquid-to-solid ratio, oxygen supply, temperature, inoculation, and sampling uncertainty. (Shiers et al., 2010; Zhang et al., 2022).

5. Column Testing: Transition from Reaction Control to Heap Physics

Column design must specify diameter, bed height, wall effects, ore loading, particle-size distribution, bulk density, irrigation flux, and air supply. Short beds risk disproportionate influence from boundary effects, while tall beds may develop axial gradients that are not visible in averaged outlet analyses. Pore water saturation, residence-time distribution, and preferential pathways determine access to reactive mineral surfaces. Meaningful comparison requires mass-balanced recovery and, where feasible, spatially resolved monitoring.

Figure 2 separates major vertical trends in an irrigated column. The conceptual zones can overlap and shift over time, so depth-averaged pregnant liquor alone cannot resolve where limitations develop.

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

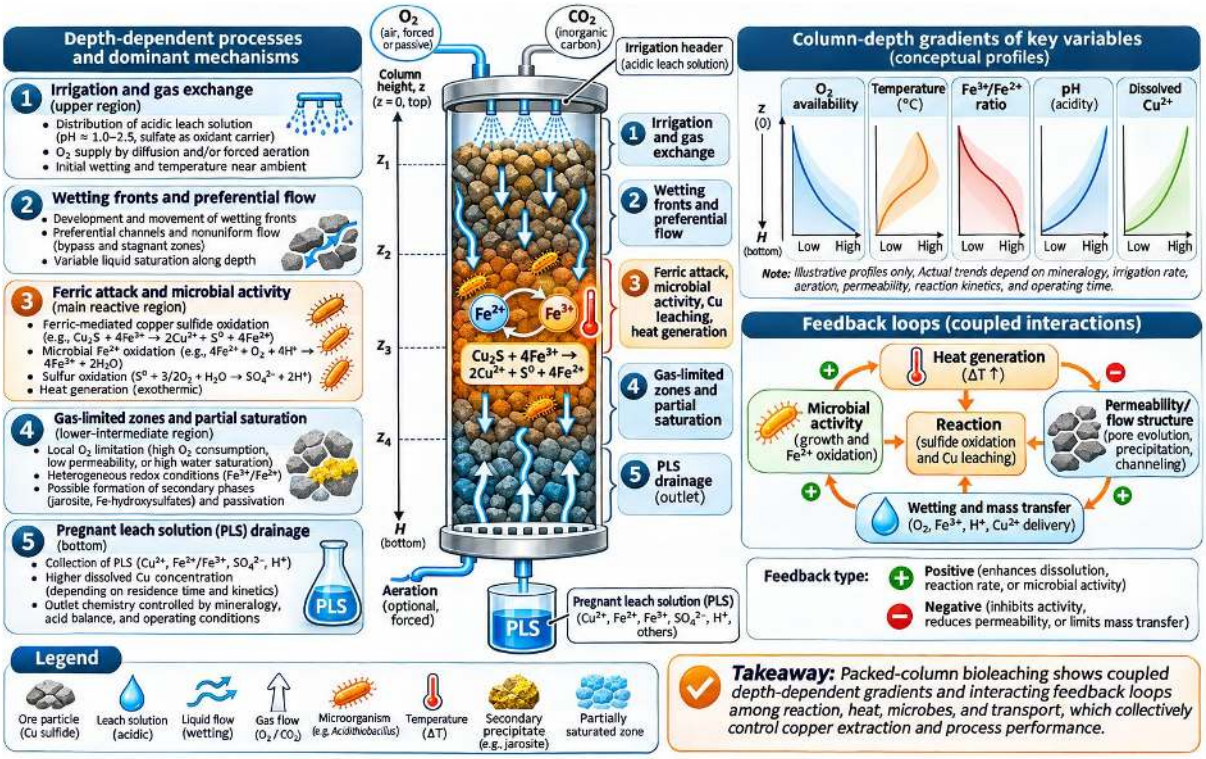


Figure 2. Column-depth gradients and feedback.

Note. Conceptual illustration prepared for this review with AI-assisted graphics; scientific content and labels require author verification before publication. No quantitative magnitude is implied.

A meaningful column experiment must expose both hydraulic and reactive heterogeneity. Flow bypass can produce rapid drainage with low mineral contact; excessive hold-up can instead obstruct gas penetration. Therefore, report height, diameter, and wall-to-particle size ratio alongside irrigation rate and bed density. Outlet chemistry alone cannot distinguish these regimes. (Bakhti et al., 2024; Chen et al., 2022; Huang et al., 2026). These sources frame the relevant mechanism or experimental question; their individual quantitative findings have not been independently verified.

A meaningful column experiment must expose both hydraulic and reactive heterogeneity. Flow bypass can produce rapid drainage with low mineral contact; excessive hold-up can instead obstruct gas penetration. Therefore, report height, diameter, and wall-to-particle size ratio alongside irrigation rate and bed density. Outlet chemistry alone cannot distinguish these regimes. (Mäkinen et al., 2019; Pereira, 2026e; Yin et al., 2011).

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

A key unresolved comparison is the degree to which the same ore, size distribution, acidity, irrigation schedule, and inoculation history have been maintained across successive scales. Without that matched basis, variation among reported recovery curves cannot be attributed uniquely to reactor geometry or mechanistic scale effects. Reports should therefore disclose feed and test conditions before benchmarking effectiveness or inferring industrial readiness.

6. Ore Preparation, Agglomeration, and Heap Permeability

Crushing and fines generation influence mineral exposure and the packed bed's hydraulic conductance in opposing directions. Agglomeration and curing can stabilize a percolating structure, but stability must be demonstrated under wetting, chemical attack, and load. The design objective is not minimum particle size; it is sustainable access to reactive particles over the required residence time. Precipitation, swelling, fines migration, and compaction should be examined together rather than treated as isolated failure modes.

The comparison in Table 3 highlights which observables are transferable and which require higher-scale verification.

Table 3. Ore preparation and bed performance

Variable	Potential benefit	Risk to quantify
Smaller PSD	Better exposure	Fines migration and plugging
Agglomeration	Stable flow paths	Attrition and breakdown
Acid curing	Early mineral conversion	Local cementation
Irrigation flux	Greater reagent delivery	Short-circuiting or flooding

Note. This review proposes a qualitative appraisal; ratings are methodological judgments, not experimentally measured recovery values.

Comparability requires a declared basis: ore source and mineralogy, particle-size distribution, geometry, irrigation and aeration, temperature, exposure time, and analytical uncertainty. Without that basis, apparent recovery agreement may conceal different transport constraints.

Comminution has opposing effects: it exposes reactive surfaces while increasing the possibility of fines migration and pore occlusion. Initial pellet strength alone does not validate agglomeration; relevant tests include wet durability, permeability under load, and permeability after secondary mineral precipitation. (Chen et al., 2020; Ghorbani et al., 2011;

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

Huang et al., 2022). These sources frame the relevant mechanism or experimental question; their individual quantitative findings have not been independently verified.

Comminution has opposing effects: it exposes reactive surfaces while increasing the possibility of fines migration and pore occlusion. Initial pellet strength alone does not validate agglomeration; relevant tests include wet durability, permeability under load, and permeability after secondary mineral precipitation. (Pereira, 2026a; Wang et al., 2021; Zhong et al., 2023).

7. Microbiology Across Experimental Scales

Microbial selection must consider indigenous populations, inoculum conditioning, acid and salt tolerance, biofilm attachment, succession, and temperature adaptation. Cell density in a vigorously mixed flask does not indicate uniform colonization within a partially saturated bed. Biomass assays should be coupled with ferrous-oxidation capacity, mineral-surface attachment, and spatial sample locations. Inference from microbial taxonomy alone is insufficient to demonstrate contribution to overall copper recovery.

Microbial assemblages should be evaluated functionally, rather than listed solely by taxonomy. Attachment, ferrous oxidation, sulfur oxidation, and stress tolerance can change independently; moreover, planktonic samples may not represent biofilms in the bed. Whenever practicable, sampling should distinguish liquid, attached, and depth-dependent populations. (Amouric et al., 2010; Bellenberg et al., 2018; Bellenberg et al., 2019). These sources frame the relevant mechanism or experimental question; their individual quantitative findings have not been independently verified.

Cross-study interpretation is complicated when some investigations characterize genes or proteins while others measure process recovery. These observations can support mechanistic hypotheses, but their predictive value requires matched mineralogy and operating conditions. (Bird et al., 2011; Bonnefoy et al., 2012; Brierley et al., 2013).

Microbial assemblages should be evaluated functionally, rather than listed solely by taxonomy. Attachment, ferrous oxidation, sulfur oxidation, and stress tolerance can change independently; moreover, planktonic samples may not represent biofilms in the bed.

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

Sampling should distinguish liquid, attached, and depth-dependent populations whenever practicable. (Buetti-Dinh et al., 2020; Díaz et al., 2018; Diao et al., 2014).

Cross-study interpretation is complicated when some investigations characterize genes or proteins while others measure process recovery. These observations can support mechanistic hypotheses, but their predictive value requires matched mineralogy and operating conditions. (Falagán et al., 2016; Flemming et al., 2016; Hedrich et al., 2016).

Microbial assemblages should be evaluated functionally, rather than listed solely by taxonomy. Attachment, ferrous oxidation, sulfur oxidation, and stress tolerance can change independently; moreover, planktonic samples may not represent biofilms in the bed. Sampling should distinguish liquid, attached, and depth-dependent populations whenever practicable. (Hedrich et al., 2011; Jerez, 2017; Johnson et al., 2012). These sources frame the relevant mechanism or experimental question; their individual quantitative findings have not been independently verified.

Cross-study interpretation is complicated when some investigations characterize genes or proteins while others measure process recovery. These observations can support mechanistic hypotheses, but their predictive value requires matched mineralogy and operating conditions. (Kaksonen et al., 2018; Liu et al., 2011; Marrero et al., 2020).

Microbial assemblages should be evaluated functionally, rather than listed solely by taxonomy. Attachment, ferrous oxidation, sulfur oxidation, and stress tolerance can change independently; moreover, planktonic samples may not represent biofilms in the bed. Sampling should distinguish liquid, attached, and depth-dependent populations whenever practicable. (Martinez et al., 2015; Nancucheo et al., 2012; Opara et al., 2022).

Cross-study interpretation is complicated when some investigations characterize genes or proteins while others measure process recovery. These observations can support mechanistic hypotheses, but their predictive value requires matched mineralogy and operating conditions. (Prescott et al., 2020; Rivera-Araya et al., 2019; Shiers et al., 2016).

Microbial assemblages should be evaluated functionally, rather than listed solely by taxonomy. Attachment, ferrous oxidation, sulfur oxidation, and stress tolerance can change

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

independently; moreover, planktonic samples may not represent biofilms in the bed. Sampling should distinguish liquid, attached, and depth-dependent populations whenever practicable. (Talla et al., 2014; Tanne et al., 2021; Vera et al., 2013). These sources frame the relevant mechanism or experimental question; their individual quantitative findings have not been independently verified.

Cross-study interpretation is complicated when some investigations characterize genes or proteins while others measure process recovery. These observations can support mechanistic hypotheses, but their predictive value requires matched mineralogy and operating conditions. (Vera et al., 2013; Yuta et al., 2021; Zhang et al., 2021).

8. Thermal, Gas-Transfer, and Hydrodynamic Phenomena

Sulfide oxidation can generate heat, while evaporation, ambient convection, precipitation, and irrigation redistribute energy. Gas transport depends on open pore networks, gas–liquid displacement, forced aeration, and oxygen uptake. A thermally favorable zone may coincide with poor oxygen accessibility; conversely, vigorous ventilation may diminish heat retention. These interactions require coupled energy, water, gas, reaction, and biological balances at bed scale.

Figure 3 presents a qualitative scale-fidelity matrix. Its ratings are interpretive judgments, not calibrated performance measures; they show why thermal, hydraulic, and gas-transfer observations become progressively more representative at larger scales.

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

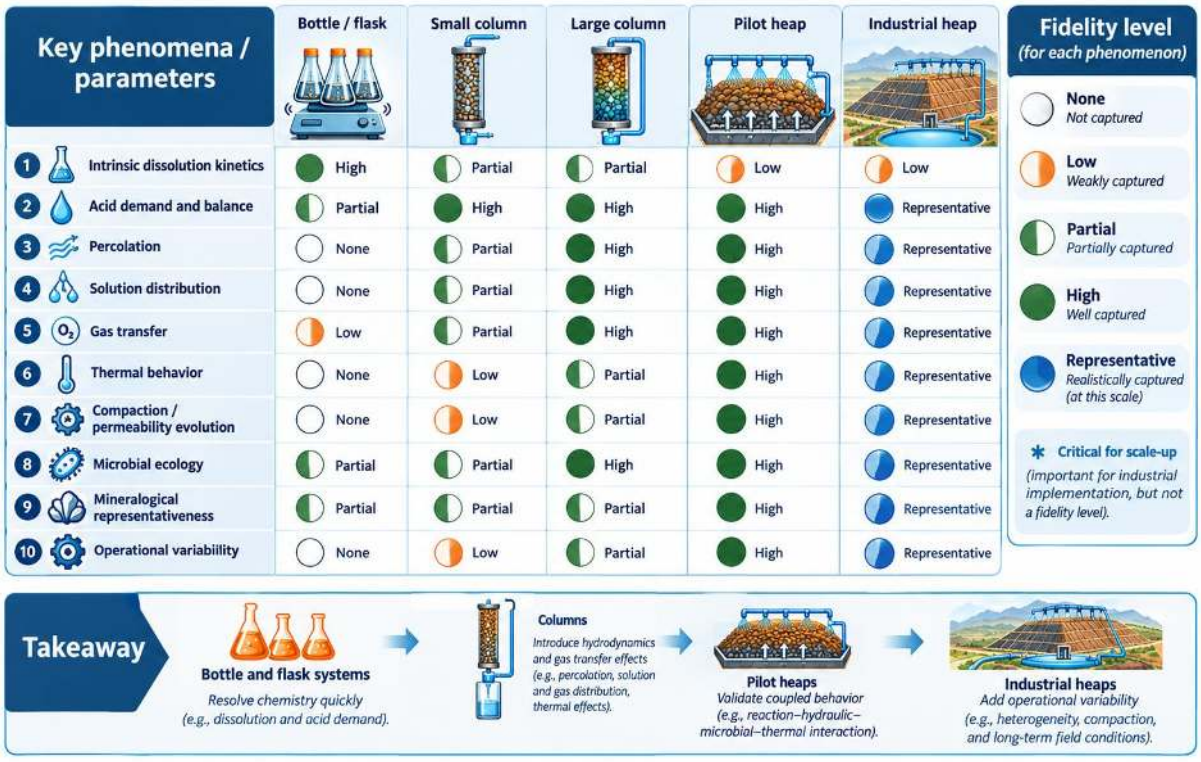


Figure 3. Scale fidelity across experimental levels.

Note. Conceptual illustration prepared for this review with AI-assisted graphics; scientific content and labels require author verification before publication. No quantitative magnitude is implied.

Heat and oxygen supply form a feedback that may be favorable over a limited temperature range yet detrimental when evaporation, precipitation, or microbial inhibition intensifies. An adequate comparison therefore requires simultaneous measurements of temperature, air flow, moisture, and oxidant demand. Figure 3 assesses the ability of successive experimental levels to reproduce these coupled effects; it does not depict a calculated heat or oxygen balance. (Banderas et al., 2013; González et al., 2026; Huynh et al., 2020). These sources frame the relevant mechanism or experimental question; their individual quantitative findings have not been independently verified.

Heat and oxygen supply form a feedback that may be favorable over a limited temperature range yet detrimental when evaporation, precipitation, or microbial inhibition intensifies. An adequate comparison therefore requires simultaneous measurements of temperature, air flow, moisture, and oxidant demand. Figure 3 assesses the ability of

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

successive experimental levels to reproduce these coupled effects; it does not depict a calculated heat or oxygen balance. (Li et al., 2019; Nie et al., 2026; Zeng et al., 2010).

9. Pilot-Scale Heap Testing

A pilot program should test operating control rather than merely reproduce a target copper-extraction figure. Ore tonnage, lift height, liner, irrigation, drainage, ventilation, and sampling geometry should reflect the intended commercial process and geological variability. Monitoring of temperature, dissolved and gaseous oxygen, moisture, solution chemistry, flow, and pressure can reveal process nonuniformity. The pilot duration must be sufficient to observe evolving flow pathways, microbial succession, and slower secondary-sulfide dissolution.

The comparison in Table 4 highlights which observables are transferable and which require higher-scale verification.

Table 4. Minimum monitoring requirements for a pilot bioheap

Domain	Observables	Interpretive purpose
Hydraulic	Flow, moisture, pressure	Uniformity and water balance
Thermal	Depth-resolved temperature	Self-heating and losses
Gas	O_2, CO_2, air flow	Transfer limitation
Microbial	Attached/planktonic populations	Biological distribution
Chemical	Cu, Fe^{2+}/Fe^{3+}, pH, sulfate	Reaction and solution balance

Note. This review provides a qualitative appraisal; ratings are methodological judgments, not experimentally measured recovery values.

Comparability requires a declared basis: ore source and mineralogy, particle-size distribution, geometry, irrigation and aeration, temperature, exposure time, and analytical uncertainty. Without that basis, apparent recovery agreement may conceal different transport constraints.

A pilot should be designed to falsify the scale-up assumptions established in column work. In addition to cumulative extraction, monitoring should detect uneven drainage, local oxygen depletion, seasonal temperature shifts, and permeability degradation. Duration must be justified against the expected reaction timescale; brief favorable operation alone is insufficient for long-term design. (Brierley et al., 2013; Demergasso et al., 2010; Lizama,

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

2023). These sources frame the relevant mechanism or experimental question; their individual quantitative findings have not been independently verified.

A pilot should be designed to falsify the scale-up assumptions established in column work. In addition to cumulative extraction, monitoring should detect uneven drainage, local oxygen depletion, seasonal temperature shifts, and permeability degradation. Duration must be justified against the expected reaction timescale; brief favorable operation alone is insufficient for long-term design. (Roberto, 2017; Roberto, 2018; Watling et al., 2015).

A key unresolved comparison is the degree to which the same ore, size distribution, acidity, irrigation schedule, and inoculation history have been maintained across successive scales. Without that matched basis, variation among reported recovery curves cannot be attributed uniquely to reactor geometry or mechanistic scale effects. Reports should therefore disclose feed and test conditions before benchmarking effectiveness or inferring industrial readiness.

10. Scaling Relationships: Bottle to Industrial Heap

Scale transfer must be parameter-specific. Acid requirement, ultimate extraction potential, and mineralogical reactivity may remain comparable after normalization, whereas permeability, oxygen distribution, temperature, compaction, and microbial ecology become fundamentally scale-sensitive. Agreement between bottle and column extraction can be accidental when different rate limitations offset each other. A sound transfer model therefore compares mechanistic observables as well as total copper recovery.

No single universal scale-up factor is physically defensible across mineralogy, irrigation, and climate. A useful transfer protocol should preserve ore population characteristics while measuring how contact efficiency, gas access, and bed temperature depart from laboratory conditions. Prediction error must be evaluated separately for recovery, acid consumption, and solution chemistry. (Beard et al., 2011; Gericke et al., 2010; Janosch et al., 2015). These sources frame the relevant mechanism or experimental question; their individual quantitative findings have not been independently verified.

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

No single universal scale-up factor is physically defensible across mineralogy, irrigation, and climate. A useful transfer protocol should preserve ore-population characteristics while measuring how contact efficiency, gas access, and bed temperature depart from laboratory conditions. Prediction error must be evaluated separately for recovery, acid consumption, and solution chemistry. (Pereira, 2026d; Ruan et al., 2013; Shang et al., 2021).

No single universal scale-up factor is physically defensible across mineralogy, irrigation, and climate. A useful transfer protocol should preserve ore population characteristics while measuring how contact efficiency, gas access, and bed temperature depart from laboratory conditions. Prediction error must be evaluated separately for recovery, acid consumption, and solution chemistry. (Watling et al., 2013).

A key unresolved comparison is the degree to which the same ore, size distribution, acidity, irrigation schedule, and inoculation history have been maintained across successive scales. Without that matched basis, variation among reported recovery curves cannot be attributed uniquely to reactor geometry or mechanistic scale effects. Reports should therefore disclose feed and test conditions before benchmarking effectiveness or inferring industrial readiness.

11. Kinetic, Reactive-Transport, and Scale-Up Modeling

Empirical extraction curves are descriptive, not sufficient for prediction outside the calibration envelope. Shrinking-core formulations, population balances, unsaturated multiphase transport, bio-oxidation kinetics, and heat balances offer complementary abstractions. Calibration on a single column without blind pilot validation leaves parameters confounded, particularly effective reaction rates and mass-transfer coefficients. Model development should report parameter identifiability, sensitivity, uncertainty, closure of mass and energy balances, and prediction intervals.

A kinetic fit to one laboratory recovery curve is a calibration result rather than model validation. Independent column or pilot datasets should test whether the model predicts transient extraction, liquid residence, oxygen demand, and temperature with parameters fixed in advance. Otherwise, increased model complexity can conceal non-identifiability. (Christel

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

et al., 2017; Hallberg et al., 2011; Jiang et al., 2021). These sources frame the relevant mechanism or experimental question; their individual quantitative findings have not been independently verified.

A kinetic fit to one laboratory recovery curve is a calibration result rather than model validation. Independent column or pilot datasets should test whether the model predicts transient extraction, liquid residence, oxygen demand, and temperature with parameters fixed in advance. Otherwise, increased model complexity can conceal non-identifiability. (Manesh et al., 2024; Petersen, 2023).

A key unresolved comparison is the degree to which the same ore, size distribution, acidity, irrigation schedule, and inoculation history have been maintained across successive scales. Without that matched basis, variation among reported recovery curves cannot be attributed uniquely to reactor geometry or mechanistic scale effects. Reports should therefore disclose feed and test conditions before benchmarking effectiveness or inferring industrial readiness.

12. Critical Synthesis, Evidence Gates, and Research Gaps

An actionable pathway comprises ore characterization, bottle screening, diagnostic columns, representative columns, large-column tests, instrumented pilot heaps, independent model validation, and commercial design. A transition to the next stage requires evidence that the current stage has resolved its main limiting mechanisms, not merely exceeded a recovery threshold. Critical gaps include standardized hydraulic characterization, direct multiscale comparisons on the same ore, time-dependent permeability, published gas-flow and thermal balances, and independent industrial verification.

The proposed gate sequence in Figure 4 frames the minimum observations needed to advance between scales; the gate thresholds are project-specific and must be determined from actual ore variability and commercial targets.

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

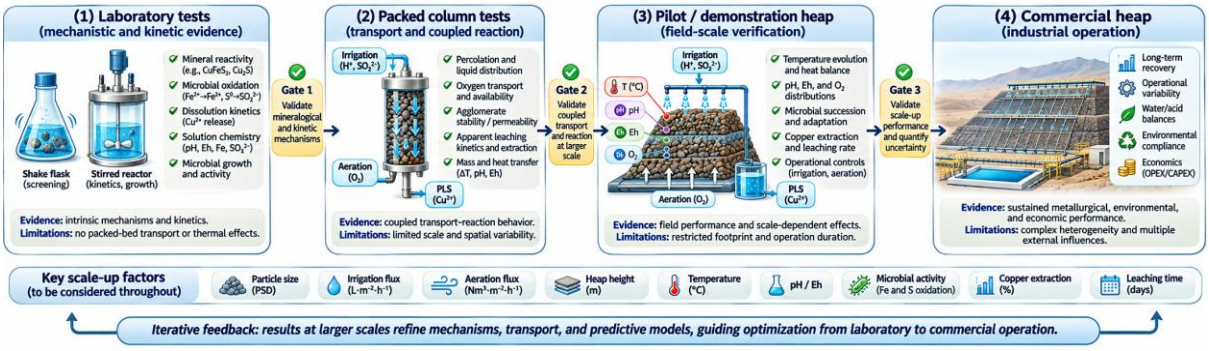


Figure 4. Go/no-go evidence gates.

Note. Conceptual illustration prepared for this review with AI-assisted graphics; scientific content and labels require author verification before publication. No quantitative magnitude is implied.

The comparison in Table 5 highlights which observables are transferable and which require higher-scale verification.

Table 5. Proposed go/no-go criteria

Transition	Required evidence	No-go signal
Bottle → column	Reaction potential and acid demand	Inhibition or nonviable consumption
Column → pilot	Stable flow, gas access, reproducible kinetics	Persistent channeling or oxygen depletion
Pilot → commercial	Heat, gas, water balances and validated model	Unexplained gradients or model failure

Note. Qualitative appraisal proposed in this review; ratings are methodological judgments, not experimentally measured recovery values.

Comparability requires a declared basis: ore source and mineralogy, particle-size distribution, geometry, irrigation and aeration, temperature, exposure time, and analytical uncertainty. Without that basis, apparent recovery agreement may conceal different transport constraints.

The research priority is matched-scale experimentation on well-characterized ore, with consistent reporting of hydrodynamics, oxygen delivery, and heat generation. Go/no-go thresholds should be set by the ore and commercial design envelope, not copied from unrelated feedstocks. The framework is a proposal for evidence gathering and should not be mistaken for an empirically validated industrial standard. (Chen et al., 2020; Ghorbani et al., 2016; Kucera et al., 2020). These sources frame the relevant mechanism or experimental question; their individual quantitative findings have not been independently verified.

JIRRS
Journal International Review of Research Studies
Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

The research priority is matched-scale experimentation on well-characterized ore, with consistent reporting of hydrodynamics, oxygen delivery, and heat generation. Go/no-go thresholds should be set by the ore and commercial design envelope, not copied from unrelated feedstocks. The framework is a proposal for evidence gathering and should not be mistaken for an empirically validated industrial standard. (Muñoz-Sepúlveda et al., 2026; Watling et al., 2016; Xingyu et al., 2016).

13. Conclusions and Outlook

Bottle-roll experiments are appropriate for identifying reaction potential and screening chemical or biological conditions, but cannot reliably predict gravity percolation, thermal feedback, or oxygen distribution. Column studies are indispensable for hydraulic and gas-transfer qualification, whereas pilots provide the minimum credible test of interacting biological, thermal, and geomechanical effects under field-like operating conditions. The most serious scale-up risks arise when extraction curves are extrapolated without demonstrating preservation of accessibility, flow, aeration, and temperature. Future programs should use explicit decision gates, matched feed characterization, instrumented experiments, independent validation, and transparent uncertainty reporting.

Declarations

Funding

This review received no specific external funding.

Conflict of Interest

The author declares no conflict of interest.

Data Availability

No new experimental datasets were generated. All references used are listed in the manuscript; bibliographic metadata were transcribed from the supplied source file.

Author Contributions

The author performed conceptualization, critical analysis, literature synthesis, visualization, and manuscript preparation.

References

Abid, Z., & Liu, Y. (2026). Bioleaching of copper sulfide ores: From microbial mechanisms to industrial applications. Separations, 13(8), 234. https://doi.org/10.3390/separations13080234

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

Ahmadi, A., Khezri, M., Abdollahzadeh, A. A., & Askari, M. (2015). Bioleaching of copper, nickel, and cobalt from the low-grade sulfidic tailings of Golgohar Iron Mine. Hydrometallurgy, 154, 1–8. https://doi.org/10.1016/j.hydromet.2015.03.006

Altinkaya, P., Mäkinen, J., Kinnunen, P., Kolehmainen, E., Haapalainen, M., & Lundström, M. (2018). Effect of biological pretreatment on metal extraction from flotation tailings for chloride leaching. Minerals Engineering, 129, 47–53. https://doi.org/10.1016/j.mineng.2018.09.012

Amouric, A., Brochier-Armanet, C., Johnson, D. B., Bonnefoy, V., & Hallberg, K. B. (2010). Phylogenetic and genetic variation among Fe(II)-oxidizing acidithiobacilli supports the view that these comprise multiple species with different ferrous iron oxidation pathways. Microbiology, 157, 111–122. https://doi.org/10.1099/mic.0.044537-0

Arpalahti, A., & Lundström, M. (2020). Water balance of a boreal black schist heap leach operation. Mine Water and the Environment, 39, 758–768. https://doi.org/10.1007/s10230-020-00694-7

Bakhti, A., Moghimi, H., Bozorg, A., Stankovic, S., Manafi, Z., & Schippers, A. (2024). Comparison of bioleaching of a sulfidic copper ore (chalcopyrite) in column percolators and in stirred-tank bioreactors, including microbial community analysis. Chemosphere, 349, 140945. https://doi.org/10.1016/j.chemosphere.2023.140945

Banderas, A., & Guiliani, N. (2013). Bioinformatic prediction of gene functions regulated by quorum sensing in the bioleaching bacterium Acidithiobacillus ferrooxidans. International Journal of Molecular Sciences, 14, 16901–16916. https://doi.org/10.3390/ijms140816901

Beard, S., Paradela, A., Albar, J. P., & Jerez, C. A. (2011). Growth of Acidithiobacillus ferrooxidans ATCC 23270 in thiosulfate under oxygen-limiting conditions generates extracellular sulfur globules by means of a secreted tetrathionate hydrolase. Frontiers in Microbiology, 2, 79. https://doi.org/10.3389/fmicb.2011.00079

Bellenberg, S., Barthen, R., Boretska, M., Zhang, R., Sand, W., & Vera, M. (2015). Manipulation of pyrite colonization and leaching by iron-oxidizing Acidithiobacillus species. Applied Microbiology and Biotechnology, 99, 1435–1449. https://doi.org/10.1007/s00253-014-6180-y

Bellenberg, S., Buetti-Dinh, A., Galli, V., Ilie, O., Herold, M., Christel, S., Boretska, M., Pivkin, I. V., Wilmes, P., Sand, W., Vera, M., & Dopson, M. (2018). Automated microscopic analysis of metal sulfide colonization by acidophilic microorganisms. Applied and Environmental Microbiology, 84, e01835-18. https://doi.org/10.1128/AEM.01835-18

Bellenberg, S., Diaz, M., Noel, N., Sand, W., Poetsch, A., Guiliani, N., & Vera, M. (2014). Biofilm formation, communication, and interactions of leaching bacteria during colonization of pyrite and sulfur surfaces. Research in Microbiology, 165, 773–781. https://doi.org/10.1016/j.resmic.2014.08.006

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

Bellenberg, S., Huynh, D., Poetsch, A., Sand, W., & Vera, M. (2019). Proteomics reveal enhanced oxidative stress responses and metabolic adaptation in Acidithiobacillus ferrooxidans biofilm cells on pyrite. Frontiers in Microbiology, 10, 592. https://doi.org/10.3389/fmicb.2019.00592

Bellenberg, S., Leon-Morales, C.-F., Sand, W., & Vera, M. (2012). Visualization of capsular polysaccharide induction in Acidithiobacillus ferrooxidans. Hydrometallurgy, 129–130, 82–89. https://doi.org/10.1016/j.hydromet.2012.09.002

Bellenberg, S., Salas, B., Ganji, S., Jorquera-Román, C., Valenzuela, M. L., Buetti-Dinh, A., Unelius, C. R., Dopson, M., & Vera, M. (2021). Diffusible signal factor signaling controls bioleaching activity and niche protection in the acidophilic, mineral-oxidizing leptospirilli. Scientific Reports, 11, 16275. https://doi.org/10.1038/s41598-021-95324-9

Bevilaqua, D., Acciari, H. A., Arena, F. A., Benedetti, A. V., Fugivara, C. S., Tremiliosi-Filho, G., & Garcia, O., Jr. (2013). Utilization of electrochemical impedance spectroscopy for monitoring bornite bioleaching. Minerals Engineering, 48, 95–101. https://doi.org/10.1016/j.mineng.2012.12.015

Bird, L. J., Bonnefoy, V., & Newman, D. K. (2011). Bioenergetic challenges of microbial iron metabolisms. Trends in Microbiology, 19, 330–340. https://doi.org/10.1016/j.tim.2011.05.001

Blake, R. C., II, & Griff, M. N. (2012). In situ spectroscopy on intact Leptospirillum ferrooxidans reveals that reduced cytochrome 579 is an obligatory intermediate in the aerobic iron respiratory chain. Frontiers in Microbiology, 3, 136. https://doi.org/10.3389/fmicb.2012.00136

Bonnefoy, V., & Holmes, D. S. (2012). Genomic insights into microbial iron oxidation and iron uptake strategies in extremely acidic environments. Environmental Microbiology, 14, 1597–1611. https://doi.org/10.1111/j.1462-2920.2011.02626.x

Borilova, S., Mandl, M., Zeman, J., Kucera, J., Pakostova, E., Janiczek, O., & Tuovinen, O. H. (2018). Can sulfate be the first dominant aqueous sulfur species formed in the oxidation of pyrite by Acidithiobacillus ferrooxidans? Frontiers in Microbiology, 9, 3134. https://doi.org/10.3389/fmicb.2018.03134

Bosecker, K. (2014). Bioleaching and biomining. In A. Schippers, F. Glombitza, & W. Sand (Eds.), Geobiotechnology I—Metal-related issues. Springer. https://doi.org/10.1007/10_2013_213

Bostelmann, H., & Southam, G. (2020). A column leaching model of low-grade chalcopyrite ore: Mineral preferences and chemical reactivity. Minerals, 10(12), 1132. https://doi.org/10.3390/min10121132

Brar, K. K., Magdouli, S., Etteieb, S., Zolfaghari, M., Fathollahzadeh, H., Calugaru, L., Komtchou, S.-P., Tanabene, R., & Brar, S. K. (2021). Integrated bioleaching-electrometallurgy for copper recovery—A critical review. Journal of Cleaner Production, 291, 125257. https://doi.org/10.1016/j.jclepro.2020.125257

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

Brierley, C. L., & Brierley, J. A. (2013). Progress in bioleaching: Part B: Applications of microbial processes by the minerals industries. Applied Microbiology and Biotechnology, 97, 7543–7552. https://doi.org/10.1007/s00253-013-5095-3

Brierley, J. A., & Brierley, C. L. (2013). Present and future commercial applications of biohydrometallurgy. Hydrometallurgy, 59, 233–239. https://doi.org/10.1016/S0304-386X(00)00162-6

Bryan, C. G., Davis-Belmar, C. S., van Wyk, N., Fraser, M. K., Dew, D., Rautenbach, G. F., & Harrison, S. T. L. (2012). The effect of CO2 availability on the growth, iron oxidation, and CO2-fixation rates of pure cultures of Leptospirillum ferriphilum and Acidithiobacillus ferrooxidans. Biotechnology and Bioengineering, 109, 1693–1703. https://doi.org/10.1002/bit.24444

Bryan, C. G., Joulian, C., Spolaore, P., Challan-Belval, S., El Achbouni, H., & d'Hugues, P. (2011). The efficiency of indigenous and designed consortia in bioleaching stirred tank reactors. Minerals Engineering, 24, 1149–1156. https://doi.org/10.1016/j.mineng.2011.03.014

Buetti-Dinh, A., Galli, V., Bellenberg, S., Ilie, O., Herold, M., Christel, S., Boretska, M., Pivkin, I. V., Wilmes, P., Sand, W., Vera, M., & Dopson, M. (2019). Deep neural networks outperform human expert's capacity in characterizing bioleaching bacterial biofilm composition. Biotechnology Reports, 22, e00321. https://doi.org/10.1016/j.btre.2019.e00321

Buetti-Dinh, A., Herold, M., Christel, S., El Hajjami, M., Bellenberg, S., Ilie, O., Wilmes, P., Poetsch, A., Sand, W., & Vera, M. (2020). Systems biology of acidophile biofilms for efficient metal extraction. Scientific Data, 7, 1–10. https://doi.org/10.1038/s41597-020-0519-2

Castro, M., Díaz, M., Moya-Beltrán, A., & Guiliani, N. (2020). Cyclic di-GMP signaling in extreme acidophilic bacteria. In S.-H. Chou, N., Guiliani, V., Lee, & Römling, U. (Eds.), Microbial cyclic di-nucleotide signaling. Springer. https://doi.org/10.1007/978-3-030-33308-9_21

Castro, M., Deane, S. M., Ruiz, L., Rawlings, D. E., & Guiliani, N. (2015). Diguanylate cyclase null mutant reveals that the C-di-GMP pathway regulates the motility and adherence of the extremophile bacterium Acidithiobacillus caldus. PLOS ONE, 10, e0116399. https://doi.org/10.1371/journal.pone.0116399

Chen, J., Zhong, S., Tang, D., & Kuang, C. (2020). Practical experience in large-scale development of Zijinshan low-grade gold-copper mine. Mining, Metallurgy & Exploration, 37, 1339–1347. https://doi.org/10.1007/s42461-020-00237-2

Chen, K., Yin, W., Rao, F., Wu, J., Zhu, Z., & Tang, Y. (2020). Agglomeration of fine-sized copper ore in heap leaching through a geopolymerization process. Minerals Engineering, 159, 106649. https://doi.org/10.1016/j.mineng.2020.106649

Chen, W., Yin, S., & Ilankoon, I. M. S. K. (2022). Effects of forced aeration on community dynamics of free and attached bacteria in copper sulphide ore bioleaching.

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

International Journal of Minerals, Metallurgy and Materials, 29(1), 59–69. https://doi.org/10.1007/s12613-020-2125-x

Christel, S., Herold, M., Bellenberg, S., El Hajjami, M., Buetti-Dinh, A., Pivkin, I. V., Sand, W., Wilmes, P., Poetsch, A., & Dopson, M. (2017). Multi-omics reveal the lifestyle of the acidophilic, mineral-oxidizing model species Leptospirillum ferriphilum. Applied and Environmental Microbiology, 84, e02091-17. https://doi.org/10.1128/AEM.02091-17

Corbett, M. K., Eksteen, J. J., Niu, X.-Z., Watkin, E. L. J., & Watling, H. R. (2017). Interactions between microorganisms and chloride in bioleaching systems: A review. Hydrometallurgy, 168, 33–48. https://doi.org/10.1016/j.hydromet.2016.10.007

Díaz, M., Castro, M., Copaja, S., & Guiliani, N. (2018). Biofilm formation by the acidophile bacterium Acidithiobacillus thiooxidans involves c-di-GMP pathway and Pel exopolysaccharide. Genes, 9, 113. https://doi.org/10.3390/genes9020113

Díaz, M., San Martin, D., Castro, M., Vera, M., & Guiliani, N. (2020). Quorum sensing signaling molecules positively regulate the c-di-GMP effector PelD encoding gene and PEL exopolysaccharide biosynthesis in the extremophile bacterium Acidithiobacillus thiooxidans. Genes, 12, 69. https://doi.org/10.3390/genes12010069

Demergasso, C., Galleguillos, F., Soto, P., Serón, M., & Iturriaga, V. (2010). Microbial succession during a heap bioleaching cycle of low-grade copper sulfides: Does this knowledge mean a real input for industrial process design and control? Hydrometallurgy, 104, 382–390. https://doi.org/10.1016/j.hydromet.2010.04.016

Diao, M., Taran, E., Mahler, S., Nguyen, T. A. H., & Nguyen, A. V. (2014). Quantifying adhesion of acidophilic bioleaching bacteria to silica and pyrite by atomic force microscopy with a bacterial probe. Colloids and Surfaces B: Biointerfaces, 115, 229–236. https://doi.org/10.1016/j.colsurfb.2013.11.047

Dong, B., Jia, Y., Zhao, H., Tan, Q., Sun, H., Jiang, C., & Ruan, R. (2022). Evidence of weak interaction between ferric iron and extracellular polymeric substances of Acidithiobacillus ferrooxidans. Hydrometallurgy, 209, 105817. https://doi.org/10.1016/j.hydromet.2022.105817

Dopson, M., & Johnson, D. B. (2012). Biodiversity, metabolism and applications of acidophilic sulfur-metabolizing microorganisms. Environmental Microbiology, 14, 2620–2631. https://doi.org/10.1111/j.1462-2920.2012.02749.x

Falagán, C., Grail, B. M., & Johnson, D. B. (2017). New approaches for extracting and recovering metals from mine tailings. Minerals Engineering, 106, 71–78. https://doi.org/10.1016/j.mineng.2016.10.008

Falagán, C., & Johnson, D. B. (2016). Acidithiobacillus ferriphilus sp. nov., a facultatively anaerobic iron- and sulfur-metabolizing extreme acidophile. International Journal of Systematic and Evolutionary Microbiology, 66, 206–211. https://doi.org/10.1099/ijsem.0.000698

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

Falagan, C., Moya-Beltran, A., Castro, M., Quatrini, R., & Johnson, D. B. (2019). Acidithiobacillus sulfuriphilus sp. nov.: An extremely acidophilic sulfur-oxidizing chemolithotroph isolated from a neutral pH environment. International Journal of Systematic and Evolutionary Microbiology, 69, 2907–2913. https://doi.org/10.1099/ijsem.0.003576

Flemming, H.-C., Wingender, J., Szewzyk, U., Steinberg, P., Rice, S. A., & Kjelleberg, S. (2016). Biofilms: An emergent form of bacterial life. Nature Reviews Microbiology, 14, 563–575. https://doi.org/10.1038/nrmicro.2016.94

Gericke, M., Govender, Y., & Pinches, A. (2010). Tank bioleaching of low-grade chalcopyrite concentrates using redox control. Hydrometallurgy, 104, 414–419. https://doi.org/10.1016/j.hydromet.2010.02.024

Ghorbani, Y., Becker, M., Mainza, A., Franzidis, J.-P., & Petersen, J. (2011). Large particle effects in chemical/biochemical heap leach processes—A review. Minerals Engineering, 24, 1172–1184. https://doi.org/10.1016/j.mineng.2011.04.002

Ghorbani, Y., Franzidis, J.-P., & Petersen, J. (2016). Heap leaching technology—Current state, innovations and future directions: A review. Mineral Processing and Extractive Metallurgy Review, 37, 73–119. https://doi.org/10.1080/08827508.2015.1115990

González, B., Díaz-Quezada, S., Bravo-Gutiérrez, M., Muñoz-Sepúlveda, A., Montserrat, S., Hernández, P., Liu, W., Vargas, T., & Estay, H. (2026). Modeling and simulation of copper sulfide chloride-based heap leaching. Hydrometallurgy, 244, 106722. https://doi.org/10.1016/j.hydromet.2026.106722

González, E., Hernández, L., Muñoz, J. A., Blázquez, M. L., Ballester, A., & González, F. (2020). Electron shuttles stimulate the reductive dissolution of jarosite by Acidiphilium cryptum. Hydrometallurgy, 194, 105351. https://doi.org/10.1016/j.hydromet.2020.105351

Hallberg, K. B., Hedrich, S., & Johnson, D. B. (2011). Acidiferrobacter thiooxydans gen. nov., sp. nov., an acidophilic, thermo-tolerant, facultatively anaerobic iron- and sulfur-oxidizer. Extremophiles, 15, 271–279. https://doi.org/10.1007/s00792-011-0359-2

Harrison, S. T. L. (2016). Biotechnologies that utilize acidophiles. In R. Quatrini & D. B. Johnson (Eds.), Acidophiles: Life in extremely acidic environments. Caister Academic Press. https://doi.org/10.21775/9781910190333

Hedrich, S., Guézennec, A.-G., Charron, M., Schippers, A., & Joulian, C. (2016). Quantitative monitoring of microbial species during bioleaching of a copper concentrate. Frontiers in Microbiology, 7, 2044. https://doi.org/10.3389/fmicb.2016.02044

Hedrich, S., & Johnson, D. B. (2013). Aerobic and anaerobic oxidation of hydrogen by acidophilic bacteria. FEMS Microbiology Letters, 349, 40–45. https://doi.org/10.1111/1574-6968.12290

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

Hedrich, S., Kermer, R., Aubel, T., Martin, M., Schippers, A., Johnson, D. B., & Janneck, E. (2018). Implementation of biological and chemical techniques to recover metals from copper-rich leach solutions. Hydrometallurgy, 179, 274–281. https://doi.org/10.1016/j.hydromet.2018.06.012

Hedrich, S., Schlömann, M., & Johnson, D. B. (2011). The iron-oxidizing proteobacteria. Microbiology, 157, 1551–1564. https://doi.org/10.1099/mic.0.045344-0

Huang, M., Li, J.-W., Zhang, M., & Li, Z.-L. (2025). Aeration-enhanced leaching mechanism and kinetics for column bioleaching of copper sulfide ores. Journal of Chemical Technology & Biotechnology, 100(9), 1897–1908. https://doi.org/10.1002/jctb.70003

Huang, M., Li, J., Zhang, M., & Lu, F. (2026). Aeration effectiveness in column bioleaching: Microbial concentration responses, porosity evolution, and copper sulfide leaching. Biochemical Engineering Journal, 225, 109925. https://doi.org/10.1016/j.bej.2025.109925

Huang, M.-Q., Zhang, M., Zhan, S.-L., Chen, L., & Xue, Z.-L. (2022). Saturated dissolved oxygen concentration in in situ fragmentation bioleaching of copper sulfide ores. Frontiers in Microbiology, 13, 821635. https://doi.org/10.3389/fmicb.2022.821635

Huynh, D., Kaschabek, S. R., & Schlömann, M. (2020). Effect of inoculum history, growth substrates, and yeast extract addition on inhibition of Sulfobacillus thermosulfidooxidans by NaCl. Research in Microbiology, 171, 252–259. https://doi.org/10.1016/j.resmic.2020.08.004

Issotta, F., Moya-Beltran, A., Mena, C., Covarrubias, P. C., Thyssen, C., Bellenberg, S., Sand, W., Quatrini, R., & Vera, M. (2018). Insights into the biology of acidophilic members of the Acidiferrobacteraceae family derived from comparative genomic analyses. Research in Microbiology, 169, 608–617. https://doi.org/10.1016/j.resmic.2018.08.001

Janosch, C., Remonsellez, F., Sand, W., & Vera, M. (2015). Sulfur oxygenase reductase (Sor) in the moderately thermoacidophilic leaching bacteria: Studies in Sulfobacillus thermosulfidooxidans and Acidithiobacillus caldus. Microorganisms, 3, 707–724. https://doi.org/10.3390/microorganisms3040707

Jerez, C. A. (2017). Biomining of metals: How to access and exploit natural resource sustainably. Microbial Biotechnology, 10, 1191–1193. https://doi.org/10.1111/1751-7915.12792

Jia, Y., Sun, H., Tan, Q., Xu, J., Feng, X., & Ruan, R. (2021). Industrial heap bioleaching of copper sulfide ore started with only water irrigation. Minerals, 11(11), 1299. https://doi.org/10.3390/min11111299

Jiang, V., Khare, S. D., & Banta, S. (2021). Computational structure prediction provides a plausible mechanism for electron transfer by the outer membrane protein Cyc2 from Acidithiobacillus ferrooxidans. Protein Science, 30, 1640–1652. https://doi.org/10.1002/pro.4106

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

Johnson, D. B. (2014). Biomining—Biotechnologies for extracting and recovering metals from ores and waste materials. Current Opinion in Biotechnology, 30, 24–31. https://doi.org/10.1016/j.copbio.2014.04.008

Johnson, D. B. (2015). Biomining goes underground. Nature Geoscience, 8, 165–166. https://doi.org/10.1038/ngeo2384

Johnson, D. B. (2018). The evolution, current status and prospects of using biotechnologies in the mineral extraction and metal recovery sectors. Minerals, 8, 343. https://doi.org/10.3390/min8080343

Johnson, D. B., Hedrich, S., & Pakostova, E. (2017). Indirect redox transformations of iron, copper, and chromium catalyzed by extremely acidophilic bacteria. Frontiers in Microbiology, 8, 211. https://doi.org/10.3389/fmicb.2017.00211

Johnson, D. B., Kanao, T., & Hedrich, S. (2012). Redox transformations of iron at extremely low pH: Fundamental and applied aspects. Frontiers in Microbiology, 3, 96. https://doi.org/10.3389/fmicb.2012.00096

Johnson, D. B., & Quatrini, R. (2020). Acidophile microbiology in space and time. Current Issues in Molecular Biology, 39, 63–76. https://doi.org/10.21775/cimb.039.063

Kaksonen, A. H., Boxall, N. J., Gumulya, Y., Khaleque, H. N., Morris, C., Bohu, T., Cheng, K. Y., Usher, K. M., & Lakaniemi, A.-M. (2018). Recent progress in biohydrometallurgy and microbial characterization. Hydrometallurgy, 180, 7–25. https://doi.org/10.1016/j.hydromet.2018.06.018

Kaksonen, A. H., Deng, X., Bohu, T., Zea, L., Khaleque, H. N., Gumulya, Y., Boxall, N. J., Morris, C., & Cheng, K. Y. (2020). Prospective directions for biohydrometallurgy. Hydrometallurgy, 195, 105376. https://doi.org/10.1016/j.hydromet.2020.105376

Khaleque, H. N., González, C., Johnson, D. B., Kaksonen, A. H., Holmes, D. S., & Watkin, E. L. J. (2020). Genome-based classification of Acidihalobacter prosperus F5 as Acidihalobacter yilgarnensis sp. nov. International Journal of Systematic and Evolutionary Microbiology, 70, 6226–6234. https://doi.org/10.1099/ijsem.0.004519

Kucera, J., Lochman, J., Bouchal, P., Pakostova, E., Mikulasek, K., Hedrich, S., Janiczek, O., Mandl, M., & Johnson, D. B. (2020). A model of aerobic and anaerobic metabolism of hydrogen in the extremophile Acidithiobacillus ferrooxidans. Frontiers in Microbiology, 11, 610836. https://doi.org/10.3389/fmicb.2020.610836

Li, Q., Becker, T., Zhang, R., Xiao, T., & Sand, W. (2019). Investigation of adhesion of Sulfobacillus thermosulfidooxidans via atomic force microscopy equipped with mineral probes. Colloids and Surfaces B: Biointerfaces, 173, 639–646. https://doi.org/10.1016/j.colsurfb.2018.10.046

Liu, W., Lin, J., Pang, X., Cui, S., Mi, S., & Lin, J. (2011). Overexpression of rusticyanin in Acidithiobacillus ferrooxidans ATCC19859 increased Fe(II) oxidation activity. Current Microbiology, 62, 320–324. https://doi.org/10.1007/s00284-010-9708-0

Lizama, H. M. (2023). In-situ leaching of copper from spent heaps. Hydrometallurgy, 215, 105997. https://doi.org/10.1016/j.hydromet.2022.105997

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

Lorenzo-Tallafigo, J., Iglesias-González, N., Romero-García, A., Mazuelos, A., Ramírez del Amo, P., Romero, R., & Carranza, F. (2022). The reprocessing of hydrometallurgical sulfidic tailings by bioleaching: The extraction of metals and the use of biogenic liquors. Minerals Engineering, 176, 107343. https://doi.org/10.1016/j.mineng.2021.107343

Mäkinen, J., Heikola, T., Salo, M., & Kinnunen, P. (2021). The effects of milling and pH on Co, Ni, Zn, and Cu bioleaching from polymetallic sulfide concentrate. Minerals, 11, 317. https://doi.org/10.3390/min11030317

Mäkinen, J., Salo, M., Khoshkhoo, M., & Kinnunen, P. (2019). Bioleaching of low-grade copper sulfide ores in columns: The role of mineralogy, irrigation and microorganisms. Minerals Engineering, 137, 208–218. https://doi.org/10.1016/j.mineng.2019.04.020

Malik, L., & Hedrich, S. (2022). Ferric iron reduction in extreme acidophiles. Frontiers in Microbiology, 12, 818414. https://doi.org/10.3389/fmicb.2021.818414

Manesh, M. J. H., Willard, D. J., John, K. M., & Kelly, R. M. (2024). Chalcopyrite bioleaching efficacy by extremely thermoacidophilic archaea leverages balanced iron and sulfur biooxidation. Bioresource Technology, 408, 131198. https://doi.org/10.1016/j.biortech.2024.131198

Marín, S., Cortés, M., Acosta, M., Delgado, K., Escuti, C., Ayma, D., & Demergasso, C. (2021). From laboratory towards industrial operation: Biomarkers for acidophilic metabolic activity in bioleaching systems. Genes, 12, 474. https://doi.org/10.3390/genes12040474

Marrero, J., Coto, O., & Schippers, A. (2020). Metal bioleaching: Fundamentals and geobiotechnical application of aerobic and anaerobic acidophiles. In N. M. Lee (Ed.), Biotechnological applications of extremophilic microorganisms (pp. 261–288). De Gruyter. https://doi.org/10.1515/9783110424331-011

Martinez-Bussenius, C., Navarro, C. A., & Jerez, C. A. (2016). Microbial copper resistance: Importance in biohydrometallurgy. Microbial Biotechnology, 10, 279–295. https://doi.org/10.1111/1751-7915.12450

Martinez, P., Vera, M., & Bobadilla-Fazzini, R. (2015). Omics on bioleaching: Current and future impacts. Applied Microbiology and Biotechnology, 99, 8337–8350. https://doi.org/10.1007/s00253-015-6903-8

Martins, F. L., & Leão, V. A. (2023). Chalcopyrite bioleaching in chloride media: A mini-review. Hydrometallurgy, 216, 105995. https://doi.org/10.1016/j.hydromet.2022.105995

Moya-Beltrán, A., Beard, S., Rojas-Villalobos, C., Issotta, F., Gallardo, Y., Ulloa, R., Giaveno, A., Degli Esposti, M., Johnson, D. B., & Quatrini, R. (2021). Genomic evolution of the class Acidithiobacillia: Deep-branching Proteobacteria living in extreme acidic conditions. ISME Journal, 15, 3221–3238. https://doi.org/10.1038/s41396-021-00995-x

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

Muñoz-Sepúlveda, A., Vargas, T., Díaz-Quezada, S., Niño, Y., Estay, H., & Montserrat, S. (2026). Heap bioleaching of copper sulfide ores: Integrated numerical assessment of environmental influences at industrial scale. Hydrometallurgy, 244, 106763. https://doi.org/10.1016/j.hydromet.2026.106763

Nancucheo, I., & Johnson, D. B. (2012). Selective removal of transition metals from acidic mine waters by novel consortia of acidophilic sulfidogenic bacteria. Microbial Biotechnology, 5, 34–44. https://doi.org/10.1111/j.1751-7915.2011.00285.x

Nie, R., Yang, X., Tian, B., Li, W., Liu, X., Wen, J., & Yang, H. (2026). Review of numerical simulations for parameter control in heap bioleaching of copper sulfide ore. Minerals, 16(6), 568. https://doi.org/10.3390/min16060568

Noguchi, H., & Okibe, N. (2020). The role of bioleaching microorganisms in saline water leaching of chalcopyrite concentrate. Hydrometallurgy, 195, 105397. https://doi.org/10.1016/j.hydromet.2020.105397

Norris, P. R., Falagan, C., Moya-Beltran, A., Castro, M., Quatrini, R., & Johnson, D. B. (2020). Acidithiobacillus ferrianus sp. nov.: An ancestral extremely acidophilic and facultatively anaerobic chemolithoautotroph. Extremophiles, 24, 329–337. https://doi.org/10.1007/s00792-020-01157-1

Opara, C. B., Blannin, R., Ebert, D., Frenzel, M., Pollmann, K., & Kutschke, S. (2022). Bioleaching of metal(loid)s from sulfidic mine tailings and waste rock from the Neves Corvo mine, Portugal, by an acidophilic consortium. Minerals Engineering, 188, 107831. https://doi.org/10.1016/j.mineng.2022.107831

Orell, A., Navarro, C. A., Rivero, M., Aguilar, J. S., & Jerez, C. A. (2012). Inorganic polyphosphates in extremophiles and their possible functions. Extremophiles, 16, 573–583. https://doi.org/10.1007/s00792-012-0457-9

Pakostova, E., Grail, B. M., & Johnson, D. B. (2018). Bio-processing of a saline, calcareous copper sulfide ore by sequential leaching. Hydrometallurgy, 179, 36–43. https://doi.org/10.1016/j.hydromet.2018.05.004

Peng, T., Liao, W., Wang, J., Miao, J., Peng, Y., Gu, G., Wu, X., Qiu, G., & Zeng, W. (2021). Bioleaching and electrochemical behavior of chalcopyrite by a mixed culture at low temperature. Frontiers in Microbiology, 12, 663757. https://doi.org/10.3389/fmicb.2021.663757

Pereira, A. C. (2026a). Agglomeration of fine ores for heap leaching: Mechanisms, design parameters, and scale-up limitations. IKR Journal of Engineering and Technology, 2(3), 1–20. https://doi.org/10.5281/zenodo.20046848

Pereira, A. C. (2026b). Bottle roll tests for kinetic evaluation of nickel ores: Capabilities, limitations, and misinterpretations—A critical review. Revista Multidisciplinar do Nordeste Mineiro, 13(7), 1–56. https://doi.org/10.66104/z4cay337

Pereira, A. C. (2026c). Do tall columns truly represent industrial heaps? A critical review of nickel heap leach testwork. International Journal of Current Science Research and Review, 9(5), 2267–2301. https://doi.org/10.47191/ijcsrr/V9-i5-05

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

Pereira, A. C. (2026d). From columns to industrial heaps: Critical design considerations for heap leach pilot plants. International Journal of Modern Research in Engineering and Technology, 11(3), 1. https://doi.org/10.5281/zenodo.18979542

Pereira, A. C. (2026e). Short column tests for nickel heap leaching: Critical review of test design, hydraulic artifacts, and scale-up reliability. Revista Multidisciplinar do Nordeste Mineiro, 13(7), 1–58. https://doi.org/10.66104/y9zx6g57

Petersen, J. (2010). Modeling of bioleach processes: Connection between laboratory, pilot and industrial scales. Hydrometallurgy, 104, 404–409. https://doi.org/10.1016/j.hydromet.2010.03.019

Petersen, J. (2023). From understanding the rate limitations of bioleaching mechanisms to improved bioleach process design. Hydrometallurgy, 221, 106148. https://doi.org/10.1016/j.hydromet.2023.106148

Prescott, R. D., & Decho, A. W. (2020). Flexibility and adaptability of quorum sensing in nature. Trends in Microbiology, 28, 436–444. https://doi.org/10.1016/j.tim.2019.12.004

Quatrini, R., & Johnson, D. B. (2018). Microbiomes in extremely acidic environments: Functionalities and interactions that allow survival and growth of prokaryotes at low pH. Current Opinion in Microbiology, 43, 139–147. https://doi.org/10.1016/j.mib.2018.01.011

Richter, C., Kalka, H., Myers, E., Nicolai, J., & Märten, H. (2018). Constraints of bioleaching in in-situ recovery applications. Hydrometallurgy, 178, 209–214. https://doi.org/10.1016/j.hydromet.2018.04.008

Rivera-Araya, J., Pollender, A., Huynh, D., Schlomann, M., Chavez, R., & Levican, G. (2019). Osmotic imbalance, cytoplasmic acidification, and oxidative stress induction support the high toxicity of chloride in acidophilic bacteria. Frontiers in Microbiology, 10, 2455. https://doi.org/10.3389/fmicb.2019.02455

Roberto, F. F. (2017). Commercial heap biooxidation of refractory gold ores—Revisiting Newmont's successful deployment at Carlin. Minerals Engineering, 106, 2–6. https://doi.org/10.1016/j.mineng.2016.09.017

Roberto, F. F. (2018). 16S rRNA gene-targeted amplicon sequence analysis of an enargite-dominant bioleach demonstration in Peru. Hydrometallurgy, 180, 271–276. https://doi.org/10.1016/j.hydromet.2018.08.005

Ruan, R., Zou, G., Zhong, S., Wu, Z., Chan, B., & Wang, D. (2013). Why Zijinshan copper bioheapleaching plant works efficiently at low microbial activity—Study on leaching kinetics of copper sulfides and its implications. Minerals Engineering, 48, 36–43. https://doi.org/10.1016/j.mineng.2013.01.002

Ruiz, L. M., Castro, M., Barriga, A., Jerez, C. A., & Guiliani, N. (2012). The extremophile Acidithiobacillus ferrooxidans possesses a c-di-GMP signaling pathway that could play a significant role in mineral bioleaching. Letters in Applied Microbiology, 54, 133–139. https://doi.org/10.1111/j.1472-765X.2011.03180.x

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

Santos, A. L., Dybowska, A., Schofield, P. F., Herrington, R. J., & Johnson, D. B. (2020). Sulfur-enhanced reductive bioprocessing of cobalt-bearing materials for base metals recovery. Hydrometallurgy, 195, 105396. https://doi.org/10.1016/j.hydromet.2020.105396

Seredkin, M., Zabolotsky, A., & Jeffress, G. (2016). In situ recovery, an alternative to conventional methods of mining: Exploration, resource estimation, environmental issues, project evaluation and economics. Ore Geology Reviews, 79, 500–515. https://doi.org/10.1016/j.oregeorev.2016.06.016

Shamsi, S., Safaee Nejad, H., Salehi, R., Zareie, E., Hamedi, S., & Mansouri, M. (2023). Investigating the effect of Cu, Fe, Si, and Ca in copper sulfide concentrate on the tank-bioleaching process: A case study. Hydrometallurgy, 222, 106185. https://doi.org/10.1016/j.hydromet.2023.106185

Shang, H., Gao, W.-C., Wu, B., & Wen, J.-K. (2021). Bioleaching and dissolution kinetics of pyrite, chalcocite, and covellite. Journal of Central South University, 28, 2037–2051. https://doi.org/10.1007/s11771-021-4751-5

Shiers, D. W., Blight, K. R., & Ralph, D. E. (2010). Sodium sulfate and sodium chloride effects on batch culture of iron-oxidizing bacteria. Hydrometallurgy, 104, 338–343. https://doi.org/10.1016/j.hydromet.2010.03.033

Shiers, D. W., Collinson, D. M., Kelly, N. J., & Watling, H. R. (2017). Copper extraction from chalcopyrite: Comparison of three non-oxidative leaching approaches. Hydrometallurgy, 167, 122–130. https://doi.org/10.1016/j.hydromet.2016.11.007

Shiers, D. W., Ralph, D. E., & Watling, H. R. (2016). A comparative study of substrate utilization by Sulfobacillus species in mixed mineral systems. Hydrometallurgy, 161, 27–36. https://doi.org/10.1016/j.hydromet.2016.01.002

Srichandan, H., Mohapatra, R. K., Parhi, P. K., & Mishra, S. (2019). Bioleaching approach for extraction of metal values from secondary solid wastes: A critical review. Hydrometallurgy, 189, 105–122. https://doi.org/10.1016/j.hydromet.2019.105122

Stanković, S., Morić, I., Pavić, A., Vojnović, S., Vasiljević, B., & Cvetković, V. (2015). Bioleaching of copper from samples of old flotation tailings (Copper Mine Bor, Serbia). Journal of the Serbian Chemical Society, 80, 391–405. https://doi.org/10.2298/JSC140411097S

Talla, E., Hedrich, S., Mangenot, S., Ji, B., Johnson, D. B., Barbe, V., & Bonnefoy, V. (2014). Insights into the pathways of iron- and sulfur-oxidation, and biofilm formation from the chemolithotrophic acidophile Acidithiobacillus ferrivorans CF27. Research in Microbiology, 165, 753–760. https://doi.org/10.1016/j.resmic.2014.08.002

Tanne, C. K., & Schippers, A. (2021). Electrochemical investigation of microbially and galvanically leached chalcopyrite. Hydrometallurgy, 202, 105603. https://doi.org/10.1016/j.hydromet.2021.105603

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

Tao, J., Liu, X., Luo, X., Teng, T., Jiang, C., Drewniak, L., Yang, Z., & Yin, H. (2021). An integrated insight into bioleaching performance of chalcopyrite mediated by microbial factors: Functional types and biodiversity. Bioresource Technology, 319, 124219. https://doi.org/10.1016/j.biortech.2020.124219

Toro, N., Moraga, C., Torres, D., Saldaña, M., Pérez, K., & Gálvez, E. (2021). Leaching chalcocite in chloride media—A review. Minerals, 11, 1197. https://doi.org/10.3390/min11111197

Vakylabad, A. B., Nazari, S., & Darezereshki, E. (2022). Bioleaching of copper from chalcopyrite ore at higher NaCl concentrations. Minerals Engineering, 175, 107281. https://doi.org/10.1016/j.mineng.2021.107281

Vargas, T., Estay, H., Arancibia, E., & Díaz-Quezada, S. (2020). In situ recovery of copper sulfide ores: Alternative process schemes for bioleaching application. Hydrometallurgy, 196, 105442. https://doi.org/10.1016/j.hydromet.2020.105442

Velásquez-Yévenes, L., Malverde, S., & Quezada, V. (2022). A sustainable bioleaching of a low-grade chalcopyrite ore. Minerals, 12(4), 487. https://doi.org/10.3390/min12040487

Vera, M., Krok, B., Bellenberg, S., Sand, W., & Poetsch, A. (2013). Shotgun proteomics study of early biofilm formation process of Acidithiobacillus ferrooxidans ATCC 23270 on pyrite. Proteomics, 13, 1133–1144. https://doi.org/10.1002/pmic.201200386

Vera, M., Schippers, A., & Sand, W. (2013). Progress in bioleaching: Fundamentals and mechanisms of bacterial metal sulfide oxidation—Part A. Applied Microbiology and Biotechnology, 97, 7529–7541. https://doi.org/10.1007/s00253-013-4954-2

Wang, L., Cheng, L., Zhang, X., Yin, S., Zhang, X., Li, H., Luo, Y., & Zhang, L. (2024). Reactive fluid flow (RFF), its hydrodynamic modeling and process control in cleaner production of copper sulfides bioleaching. Journal of Cleaner Production, 441, 140792. https://doi.org/10.1016/j.jclepro.2024.140792

Wang, L., Yin, S., Deng, B., & Wu, A. (2022). Copper sulfides leaching assisted by acidic seawater-based media: Ionic strength and mechanism. Minerals Engineering, 175, 107286. https://doi.org/10.1016/j.mineng.2021.107286

Wang, L., Yin, S., & Wu, A. (2021). Ore agglomeration behavior and its key controlling factors in heap leaching of low-grade copper minerals. Journal of Cleaner Production, 279, 123705. https://doi.org/10.1016/j.jclepro.2020.123705

Watling, H. R. (2014). Review of biohydrometallurgical metals extraction from polymetallic mineral resources. Minerals, 5, 1–60. https://doi.org/10.3390/min5010001

Watling, H. R., Collinson, D. M., Corbett, M. K., Shiers, D. W., Kaksonen, A. H., & Watkin, E. L. J. (2016). Saline-water bioleaching of chalcopyrite with thermophilic, iron(II)- and sulfur-oxidizing microorganisms. Research in Microbiology, 167, 546–554. https://doi.org/10.1016/j.resmic.2016.05.003

Watling, H. R., Collinson, D. M., Shiers, D. W., Bryan, C. G., & Watkin, E. L. J. (2013). Effects of pH, temperature, and solids loading on microbial community structure

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

during batch culture on a polymetallic ore. Minerals Engineering, 48, 68–76. https://doi.org/10.1016/j.mineng.2012.10.014

Watling, H. R., Shiers, D. W., & Collinson, D. M. (2015). Extremophiles in mineral sulfide heaps: Some bacterial responses to variable temperature, acidity, and solution composition. Microorganisms, 3, 455–477. https://doi.org/10.3390/microorganisms3030455

Watling, H. R., Shiers, D. W., Li, J., & Watkin, E. L. J. (2016). Effect of chloride on microorganisms relevant to bioleaching and on copper sulfide dissolution. Hydrometallurgy, 161, 52–61. https://doi.org/10.1016/j.hydromet.2016.01.005

Whitworth, A. J., Vaughan, J., Southam, G., van der Ent, A., Nkrumah, P. N., Ma, X., & Parbhakar-Fox, A. (2022). Review on metal extraction technologies suitable for critical metal recovery from mining and processing wastes. Minerals Engineering, 182, 107537. https://doi.org/10.1016/j.mineng.2022.107537

Xingyu, L., Bowei, C., Jinghe, C., Mingjiang, Z., Jiankang, W., & Dianzuo, W. (2016). Spatial variation of microbial community structure in the Zijinshan commercial copper heap bioleaching plant. Minerals Engineering, 94, 76–82. https://doi.org/10.1016/j.mineng.2016.05.008

Yin, S., Wang, L., Kabwe, E., Chen, X., Yan, R., An, K., Zhang, L., & Wu, A. (2018). Copper bioleaching in China: Review and prospect. Minerals, 8, 32. https://doi.org/10.3390/min8020032

Yin, S., Wu, A., Li, X., & Wang, Y. (2011). Mathematical model for coupled reactive flow and solute transport during heap bioleaching of copper sulfide. Journal of Central South University, 18, 1434–1440. https://doi.org/10.1007/s11771-011-0858-4

Yuta, I., West, A. C., Banta, S., & Kelly, R. M. (2021). Glutathione synthetase overexpression in Acidithiobacillus ferrooxidans improves halotolerance of iron oxidation. Applied and Environmental Microbiology, 87, e01518-21. https://doi.org/10.1128/AEM.01518-21

Zeng, W., Qiu, G., Zhou, H., & Liu, X. (2010). Bioleaching of chalcopyrite by pure and mixed cultures of moderately thermophilic microorganisms. Minerals Engineering, 23, 883–889. https://doi.org/10.1016/j.mineng.2010.05.010

Zhang, R., Hedrich, S., Jin, D., Breuker, A., & Schippers, A. (2021). Sulfobacillus harzensis sp. nov., an acidophilic bacterium inhabiting mine tailings from a polymetallic mine. International Journal of Systematic and Evolutionary Microbiology, 71, 004871. https://doi.org/10.1099/ijsem.0.004871

Zhang, R., Hedrich, S., Römer, F., Goldmann, D., & Schippers, A. (2020). Bioleaching of cobalt from Cu/Co-rich sulfidic mine tailings from the polymetallic Rammelsberg mine. Hydrometallurgy, 197, 105443. https://doi.org/10.1016/j.hydromet.2020.105443

JIRRS
Journal International Review of Research Studies

Received: 13/06/2026 - **Accepted:** 07/11/2026
Vol: 1.10
DOI: 10.66104/y7ja7k36
Pages: 1-37

Zhang, R., & Schippers, A. (2022). Stirred-tank bioleaching of copper and cobalt from mine tailings in Chile. Minerals Engineering, 180, 107514. https://doi.org/10.1016/j.mineng.2022.107514

Zhao, H., Wang, J., Hu, M., Qin, W., Zhang, Y., & Qiu, G. (2013). Synergistic bioleaching of chalcopyrite and bornite in the presence of Acidithiobacillus ferrooxidans. Bioresource Technology, 149, 71–76. https://doi.org/10.1016/j.biortech.2013.09.022

Zhong, W., Zhong, S., Tang, D., Chi, X., & Weng, W. (2023). Understanding the mechanism of microcrack-enhanced bioleaching of copper. Hydrometallurgy, 218, 106045. https://doi.org/10.1016/j.hydromet.2023.106045