Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

Microwave Pretreatment of Refractory Gold Ores: Mineralogical Selectivity, Thermal Fracturing, and Hybrid Processing Strategies

Antonio Clareti Pereira, Ph.D.
Department of Graduate Program in Materials Engineering
Federal University of Ouro Preto (UFOP)
Ouro Preto, Minas Gerais, Brazil
E-mail: claretipereira@gmail.com
ORCID: https://orcid.org/0000-0001-8115-4279

Abstract

Researchers have investigated microwave pretreatment to increase gold accessibility in refractory sulfide, carbonaceous, and composite ores. This critical review examines whether improvements arise from genuine mineral-selective electromagnetic energy deposition, ordinary heating, mechanical weakening, chemical oxidation, or combinations of these effects. It integrates mineralogical diagnosis, dielectric coupling, microcrack formation, sulfide transformation, subsequent cyanidation, non-cyanide leaching, hybrid oxidation, and continuous-reactor design. It gives particular attention to fair comparisons with temperature-matched conventional heating, ultrafine grinding, pressure oxidation, and biological pretreatment. The evidence is heterogeneous: some experiments demonstrate faster leaching or easier breakage, but results are frequently reported without comparable electrical energy balances, continuous-throughput data, comprehensive arsenic–sulfur capture, or paired mineralogical measurements. A stage-gated framework proposes that mineralogy and microwave absorptivity first establish technical plausibility, controlled experimentation identifies the operative mechanism, and integrated energy, metallurgical, environmental, and financial accounting determines feasibility. Microwave application is most defensible for responsive and suitably concentrated feeds where measurable downstream savings exceed treatment and off-gas-control costs. The review identifies validated multi-physics models, mineralogical variability, realistic reactor loading, and comparative pilot testing as the most consequential research needs.

Keywords: refractory gold ores; microwave pretreatment; dielectric heating; thermal microcracking; selective oxidation; hybrid hydrometallurgy

Highlights

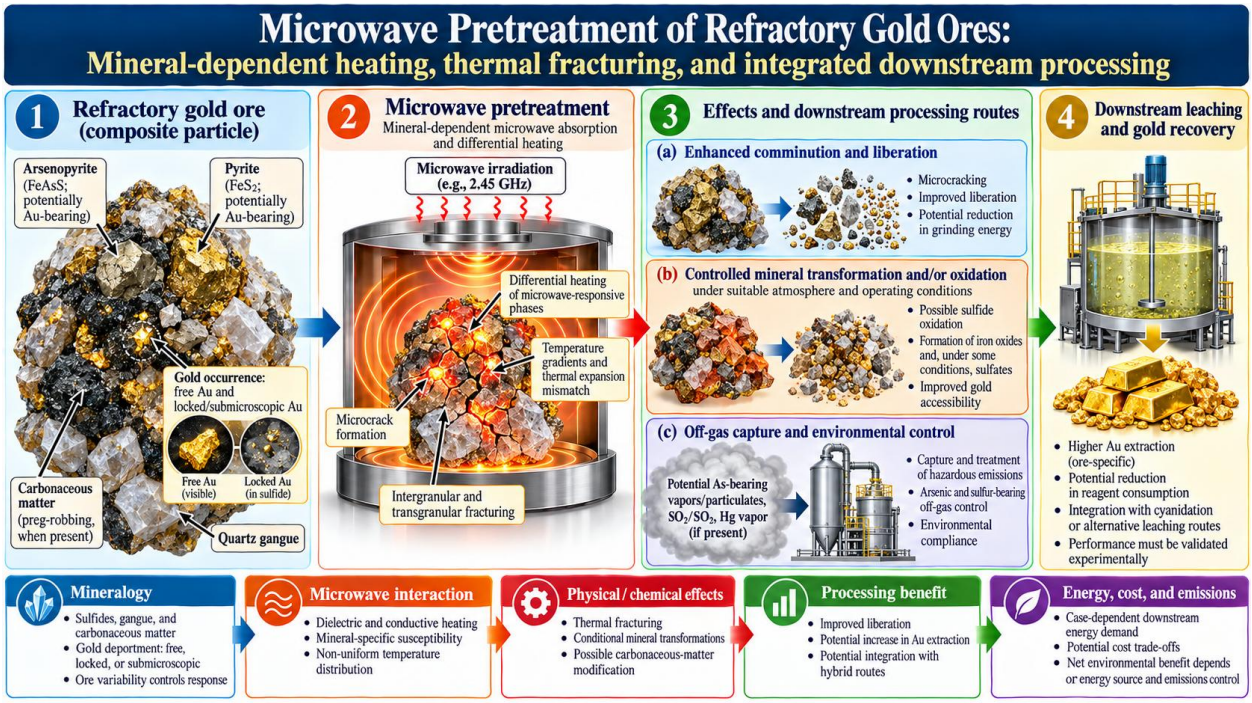
- Microwave gains must be separated from temperature-matched conventional heating.
- Mineral assemblage governs absorption, fracturing, oxidation, and gold liberation.
- Hybrid routes can improve extraction but must include off-gas and reagent accounting.
- Scale-up decisions require continuous tests and system-level energy–economic validation.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

Graphical abstract



1. Introduction

Refractoriness refers to inadequate gold extraction by conventional leaching because gold is occluded within sulfides or gangue, locked at submicroscopic scales, associated with carbonaceous preg-robbers, or exposed to competing, reagent-consuming phases. Direct cyanidation can therefore underperform even when the head grade is commercially attractive. Mineralogical diagnosis and a comparative flowsheet must precede a pretreatment recommendation (Guner et al., 2023; Pereira, 2025, 2026d, 2026e).

Microwave irradiation deposits electromagnetic energy preferentially in susceptible phases; however, preferential absorption does not automatically imply a unique nonthermal reaction pathway. Improvements in comminution, liberation, and extraction may reflect differential thermal expansion, overall temperature, oxidation atmosphere, or combinations of these effects (Amankwah & Ofori-Sarpong, 2011; Amankwah & Ofori-Sarpong, 2020; Chen et al., 2024; Shahbazi, 2026). Figure 1 summarizes the causal chain, whereas Figure 2

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

distinguishes fracture from chemical transformation. Figure 3 maps candidate hybrid flowsheets, Figure 4 depicts the non-monotonic severity window, and Figure 5 presents the proposed evidence-based decision sequence. Tables 1–7 compare material response, experimental evidence, reaction changes, cyanidation, hybrid alternatives, continuous engineering, and integrated assessment.

The central question is therefore not whether microwaves can heat ores, but under what feed-specific conditions they produce greater technically and economically useful effects than equivalent conventional thermal, mechanical, oxidative, and biological treatments. This is a critical synthesis of the bibliography assembled for this review; references from non-gold mineral systems are used only to support general physical or engineering mechanisms, not gold extraction claims.

1.1. Review Methods

Review design and evidence sources. This critical narrative review synthesizes the peer-reviewed research and engineering literature included in the reference list. The authors appraised evidence based on feed mineralogy, experimental design, thermal-control adequacy, demonstrated mechanism, electrical-energy boundary, emissions management, and downstream metallurgical relevance. The source bibliography does not document database-specific search histories, the final execution date, or formal screening decisions. Consequently, the study does not claim systematic-review completeness, and a reproducible search log must be supplied before submission if the journal requires it.

Reproducible search approach. Representative Boolean expressions suitable for reproducing the topic coverage include ("refractory gold" AND (microwave OR dielectric) AND (pretreatment OR roasting)); ((pyrite OR arsenopyrite) AND microwave AND (oxidation OR microcrack*)); ("gold ore" AND microwave AND (grindability OR cyanidation OR leaching)); (microwave AND ore AND ("absorbed energy" OR "reflected power" OR "scale-up")); and (("refractory gold" OR "double refractory") AND (POX OR BIOX OR roasting OR "ultrafine grinding") AND comparison). These strings are a transparent reproducibility

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

template, not a retrospectively certified search log. Screening should prioritize relevant peer-reviewed material with a clear feed description and checkable experimental or engineering methods, exclude preprints and duplicates, and assess reviews separately from the primary data underlying their conclusions. No numeric search-result or exclusion counts are asserted.

Evidence hierarchy and limitations. Four evidence classes were distinguished: (i) tests on refractory gold ores or concentrates, (ii) tests on other gold-bearing materials, (iii) analogous experiments on nongold mineral or rock systems, and (iv) general reactor and scale-up engineering. The latter two classes support physical plausibility and experimental design, not quantitative claims of improved refractory-gold recovery. This classification is an author-developed qualitative appraisal; it was not independently dual-screened, and no inter-rater reliability statistic is claimed. Selection bias remains possible because a complete screening ledger is unavailable.

Compared with Shahbazi's (2026) broad survey of microwave-assisted gold extraction, this work's distinctive contribution is an explicit causal test of microwave-specific advantages. The appraisal links thermal-history-matched controls, quantified mineralogical change, complete arsenic/sulfur inventories, wall-plug system energy, saleable gold rather than dissolution alone, continuous-reactor validation, and an author-developed stage-gated decision framework. This is a critical narrative synthesis, not a systematic review or meta-analysis.

2. Mineralogical Basis of Gold Refractoriness

2.1. Host minerals, associations, and diagnostic liberation

Gold locked in pyrite or arsenopyrite may remain inaccessible after ordinary grinding; gold associated with pyrrhotite, chalcopyrite, or reactive iron oxides may consume additional oxygen, cyanide, or other reagents. Free gold, finely disseminated inclusions, and grain-boundary gold cannot be treated as one population. Automated mineralogy, reflected-light microscopy, SEM-based mapping, and sequential diagnostic leaching distinguish physical

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

encapsulation from chemically adverse conditions (Chai et al., 2025; Guner et al., 2023; Ma et al., 2023; Navas Jaramillo & Gonzalez Zuñiga, 2025; Pereira, 2025).

2.2. Silicates, carbonaceous matter, and double refractoriness

Quartz-rich or silicate-encapsulated gold may need interface fracture rather than bulk sulfide decomposition. Carbonaceous matter may adsorb dissolved gold complexes, so new fractures alone need not eliminate preg-robbing. Double-refractory feeds require simultaneous evaluation of physical occlusion and carbon activity; oxidation can expose gold yet alter the carbon surface or create new secondary phases (Jin et al., 2019; Konadu et al., 2020; Li et al., 2021c; Pereira, 2026d; Pereira, 2026e; Wang et al., 2019b; Xiao et al., 2022b; Xiao et al., 2022a).

The composition, texture, grain size, and connectivity of microwave-responsive minerals predict performance better than total sulfide content alone. Figure 1 makes the diagnostic–mechanistic sequence explicit; no universal mineral susceptibility ranking is assumed.

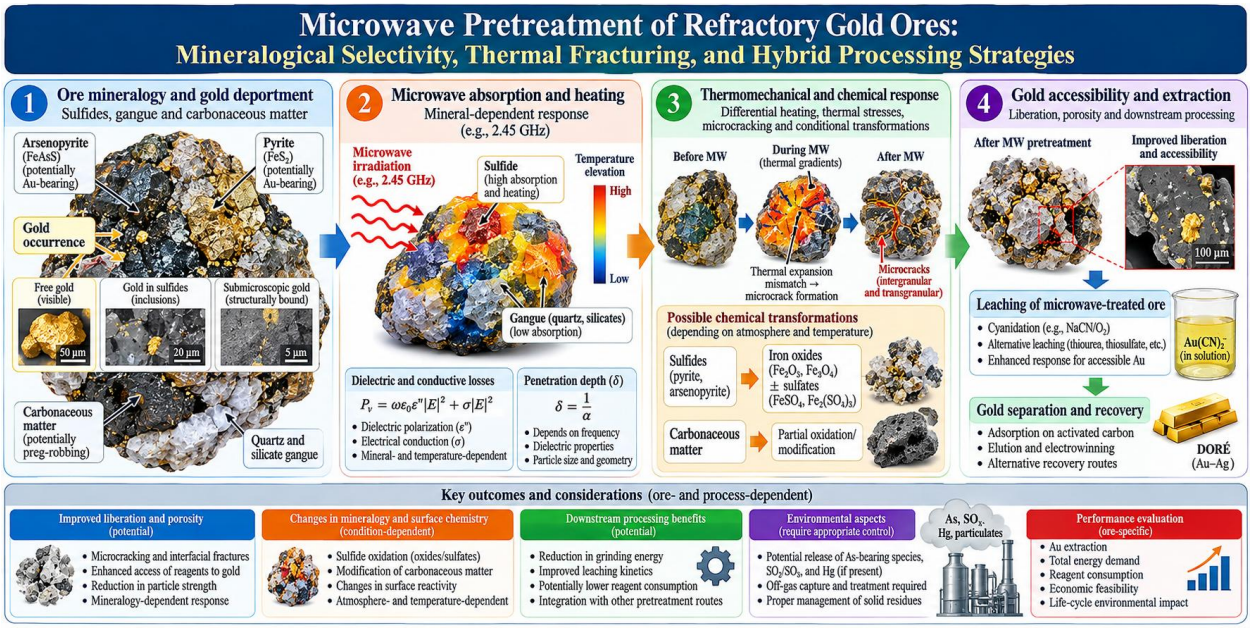


Figure 1. Mineralogy-to-extraction mechanism map for microwave pretreatment.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

Note. Author-developed conceptual synthesis based on principles discussed by Amankwah and Ofori-Sarpong (2011), Chen et al. (2024), and Shahbazi (2026); not reproduced from an existing figure.

Dielectric reporting should specify irradiation frequency, sample temperature, ε′r, ε″r, tan δ (where applicable), electrical conductivity and its treatment in the loss convention, moisture, bulk density, porosity, and magnetic-loss contributions when relevant. Response should be measured over the treatment temperature interval rather than inferred only from room-temperature data. A distinct nonthermal microwave mechanism must not be claimed when thermal history, unresolved local gradients, phase evolution, or mass-transfer effects can explain the observations.

3. Fundamentals of Microwave–Mineral Interaction

3.1. Complex permittivity and energy coupling

For a nonmagnetic, approximately homogeneous effective medium, complex relative permittivity can be expressed as $\varepsilon^*_r = \varepsilon'_r - j\varepsilon''_r$. A local dielectric-loss approximation is $p = 2\pi f \varepsilon_0 \varepsilon''_r |E_{rms}|^2$, with conductivity either represented as an additional term or absorbed into effective loss; mixing both conventions double-counts losses. Actual field distributions also depend on magnetic response, conductivity, geometry, heterogeneity, applicator design, and temperature-dependent properties (Chen et al., 2024; Gutiérrez-Cano et al., 2022; Lin et al., 2022; Lin et al., 2020; Pickles & Lu, 2022).

Penetration depth is not a fixed mineral constant; it changes with frequency, temperature, phase evolution, porosity, and moisture. Different field boundary conditions mean nominal magnetron output is an inadequate proxy for energy absorbed by the ore. Measured reflected power and applicator efficiency must be incorporated (Ahmadihosseini et al., 2022; Pressacco et al., 2022; Pressacco et al., 2023; Shadi et al., 2023).

3.2. Differential versus uniform heating

A temperature difference between sulfides and surrounding gangue can generate local stresses, but macroscopic infrared or single-point thermocouple readings may not resolve hot

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

spots. Conversely, intense bulk heating can yield equivalent oxidation kinetics without any distinctive selective-fracture mechanism. Controlled conventional-heating experiments should reproduce relevant thermal histories, not merely nominal terminal temperatures (Adewuyi et al., 2020; Adewuyi et al., 2024; He et al., 2021; Kato et al., 2022; Yang et al., 2023).

Table 1 summarizes the relevant evidence dimensions and makes explicit the principal limitations for comparing microwave and conventional processing.

Table 1. Qualitative microwave response and evidentiary limitations of selected mineral groups.

Phase/texture	Qualitative coupling expectation	Processing implication	Key verification
Pyrite/arsenopyrite	Variable; strongly temperature- and chemistry-dependent	Local heating; possible sulfide transformation	Dielectric data, XRD, sulfur/arsenic mass balance
Pyrrhotite/magnetite	Potentially strong electromagnetic coupling	Heating localization and stress concentration	Magnetic and dielectric response by temperature
Quartz / common silicates	Often relatively weak losses when dry	Stress contrast against absorber grains	Moisture, thermal expansion, liberation
Carbonaceous phases	Highly variable by carbon structure	Potential heating and preg-robbing interactions	Raman/carbon speciation and preg-robbing tests
Composite ore particles	Emergent effective response	Interface cracking or uneven reaction	3D texture and local temperature mapping

Note. Qualitative screening categories only. No universal numerical permittivity values are assigned because conditions and measurement frequencies differ. Conceptual synthesis adapted from the literature, particularly Chen et al. (2024), Lin et al. (2022), and Shahbazi (2026).

These screening-level descriptions should not be interpreted as intrinsic dielectric rankings. Temperature, moisture, frequency, grain connectivity, and atmospheric conditions must be measured for each feed.

4. Microwave Response of Gold-Bearing Minerals

4.1. Sulfides and iron oxides

Sulfide-bearing and iron-bearing grains may behave as preferential sinks of electromagnetic energy, although phase identity alone does not establish loss tangent or effective absorption. Pyrite decomposition, arsenopyrite oxidation, and pyrrhotite-associated

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

phase changes depend on oxygen potential and heating trajectory. Iron oxides formed in situ can subsequently modify electromagnetic coupling, making response dynamic rather than a fixed initial property (Diaz et al., 2016; Hao et al., 2021; Hapid et al., 2024a; Jaansalu & Pickles, 2025; Lin et al., 2023; Zhang et al., 2022b; Zhang et al., 2019).

4.2. Quartz, gangue, carbon, and composites

Microfracture claims should quantify crack number density and representative crack length/volume, interfacial versus transgranular fractions, pore connectivity and/or porosity, and modal mineral liberation on matched feed splits. Comminution and Au recovery should be compared at equivalent final particle-size distributions, or at equivalent total process energy with their distinct products explicitly reported.

A weakly absorbing gangue can experience substantial secondary conductive heat transfer from sulfide inclusions. Stress concentrates around heterogeneities, while moisture may temporarily dominate absorption. Results from granite, basalt, sandstone, and other hard rocks establish plausible fracture processes, not measured performance in refractory gold ore (Li et al., 2021b; Liang et al., 2023; Lu et al., 2020; Ma et al., 2024; Wang et al., 2023; Wang et al., 2021; Xu et al., 2021a; Xu et al., 2021b; Yuan et al., 2021; Zhang et al., 2024).

Any comparison between synthetic and real ore should document grain contacts and absorbers, because isolated-phase dielectric parameters rarely capture a multiply connected, reactive composite. Carbon introduces both heterogeneous heating and complications from gold-complex adsorption (Kafashi et al., 2025; Okibe et al., 2022; Wu et al., 2025).

5. Thermal Stress, Microcracking, and Liberation Mechanisms

5.1. Crack initiation and mechanical response

Transient temperature gradients and dissimilar thermal expansion coefficients can initiate grain-boundary or transgranular fractures, depending on grain size, mineral hardness, and existing defects. An apparent reduction in breakage energy may be caused by enhanced

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

fissuring, dehydration, or changed particle-size distribution; measurable crack density and mineral liberation are needed to establish the mechanism (Ahmadihosseini et al., 2025; Batchelor et al., 2017; Buttress et al., 2017; Jiménez Tovar et al., 2022; Rasyid et al., 2023; Seflek & Bayat, 2018).

Early experiments on gold-bearing ores reported improved grindability and cyanide response after irradiation, but the tested feed and operating regime do not generalize to all refractory concentrates. In the free-milling ore studied by Amankwah and Ofori-Sarpong (2011), they reported a 31.2% reduction in crushing strength and achieved approximately 95% extraction sooner than the untreated comparator; that observation alone does not demonstrate an industrial net-energy advantage (Amankwah & Ofori-Sarpong, 2011).

5.2. Distinguishing fracture benefits from chemical benefits

Micro-CT, SEM, automated mineralogy, XRD, and diagnostic leaching should be performed on matched aliquots before and after treatment. Gold extraction gains without statistically measurable extra liberation can instead reflect phase transformation or chemical changes. Figure 2 differentiates microcrack-driven liberation from chemical transformation and identifies measurements needed to distinguish the two mechanisms.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

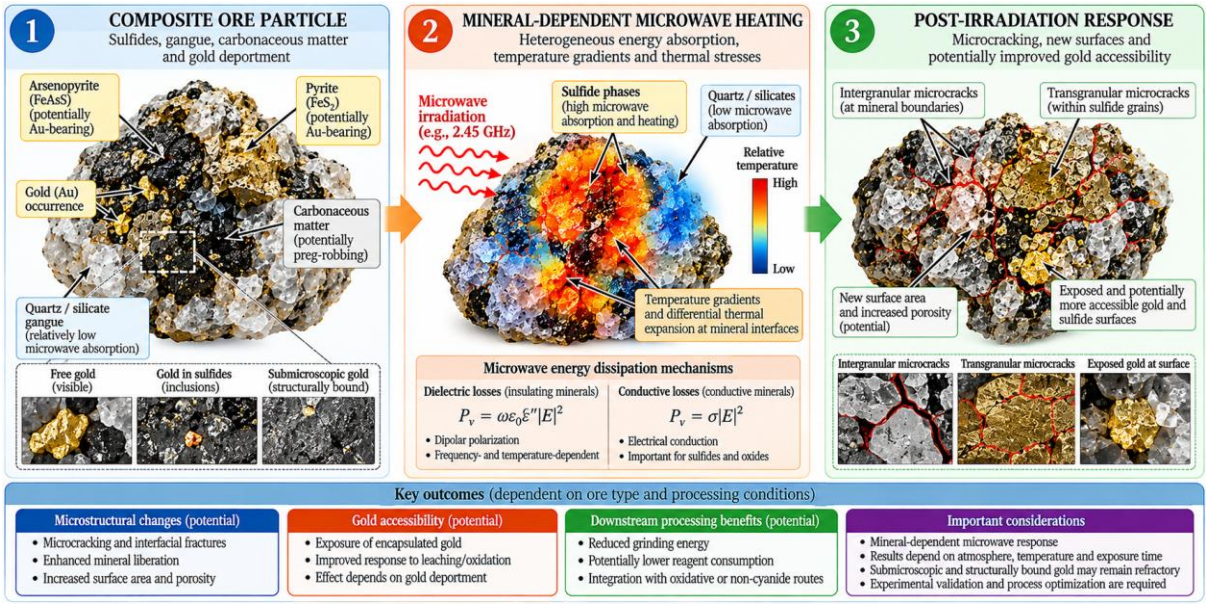


Figure 2. Differential energy absorption and potential microfracture formation in composite particles. *Note.* Author-developed conceptual illustration adapted from the mechanistic discussions of Amankwah and Ofori-Sarpong (2011), Lin et al. (2023), and Pressacco et al. (2022).

For each element i ∈ {As, S}, a minimum closure is M_i,feed = M_i,treated solids + M_i,captured dust + M_i,condensate + M_i,scrubber liquor/sludge + M_i,vented gas + M_i,unaccounted. Each stream should include its measured mass and element concentration, sampling uncertainty, and closure residual. Loss from the calcine is a redistribution, not evidence of immobilization or harmless removal.

6. Microwave-Induced Mineralogical and Chemical Transformations

6.1. Oxidation, decomposition, and passivation

Under oxidizing atmospheres, pyritic and arsenopyritic phases may transform toward iron oxides while producing sulfur- and arsenic-bearing volatile or condensed species. Under inert or reducing conditions, mineral reactions and sulfur pathways can differ materially. Thermal exposure may also produce sintering, surface oxidation, stable passivating layers, or reactive sulfur species that complicate subsequent cyanidation (Amankwah & Ofori-Sarpong, 2020; Diaz et al., 2016; Hapid et al., 2026; Hapid et al., 2024a; Hapid et al., 2024b; Hapid et

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

al., 2024c; Ma et al., 2010; Mao et al., 2026; Qin et al., 2021; Zhang et al., 2022b; Zhang et al., 2021).

Porosity evolution can improve reagent access, but phase-boundary closure and reaction-product coatings may reverse gains at excessive severity. These mechanistic distinctions motivate the qualitative regimes illustrated in Figure 4 and summarized in Table 2.

Table 2. Transformation mechanisms and recommended analytical confirmation.

Candidate transformation	Potential benefit	Potential penalty	Minimum verification
Sulfide oxidation	Unlocking submicroscopic Au	Acid generation; As/S emissions	XRD, XANES or microscopy; gas capture balance
Intergranular fracture	Enhanced liberation and permeability	Unchanged chemically locked Au	Micro-CT; MLA/QEMSCAN; grinding response
Carbon oxidation	Lower preg-robbing capacity	Au redistribution; energy costs	Organic/elemental carbon and adsorption testing
Iron oxide formation	Reduced sulfide locking	Sintering or ferric coatings	Quantitative phase analysis and surface microscopy
Sulfate/sulfur conversion	Possible reactive accessibility	Cyanide/oxygen demand	Total S and aqueous speciation

Note. Mechanisms are possible, not inevitable. Adapted conceptually from Hapid et al. (2024), Zhang et al. (2022), and Li et al. (2022).

The candidate outcomes are not mutually exclusive: cracking, oxidation, and passivation may occur together. Matched thermal controls and phase-resolved mass balances are essential for causal attribution.

The accounting boundary should extend from head sample through dissolution, solution purification, metal recovery, and saleable Au. Compare identical leaching solution chemistry, oxygen availability, pH, residence time, final PSD, reagent additions, and gold recovery method. Report cyanide or alternative lixiviant consumption, lime/neutralizing reagents, oxidants, wash water, dissolved Fe/Cu, impurity separation, and residue-management demand; Au dissolved into solution must not be equated with saleable Au recovered.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

6.2. Arsenic and sulfur mass balances

Roasting is not a clean process unless it measures and controls volatilized arsenic, sulfur oxides, particulates, and condensed residues. Reported sulfur conversion should be interpreted with gas-phase and solid-phase balances; a decline in solid-phase arsenic does not constitute safe immobilization. Waste stabilization and environmental monitoring requirements remain central (Bare et al., 2022; Espinoza-Martínez et al., 2025; Pereira, 2026a; Shi et al., 2025).

7. Microwave Pretreatment Followed by Cyanidation

7.1. Metallurgical response and confounders

Microwave-assisted routes have improved leach kinetics or recovery for selected ore and tailings types; however, published tests vary in irradiated charge mass, particle size, power, time, oxidation atmosphere, and post-treatment leaching conditions. A convincing response comparison requires matching pH, dissolved oxygen, particle-size distribution, residence time, and initial accessible gold (Cho et al., 2020b; Cho et al., 2020a; Choi et al., 2017; Li et al., 2020; Li et al., 2021a; Sapinov et al., 2026).

Cyanide and lime consumption, metal dissolution, and adsorption on carbonaceous material should accompany gold recovery. Gains obtained after a more aggressive roast may require substantial extra neutralization, or can be offset by dissolved copper and iron species. A reagent balance is therefore as important as the Au extraction percentage (Matar et al., 2026; Mutimutema et al., 2022; Pereira, 2026b; Pereira, 2026f; Pereira et al., 2017; Pereira et al., 2018).

Table 3 summarizes the relevant evidence dimensions and makes explicit the principal limitations for comparing microwave and conventional processing.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

Table 3. Selected direct gold-system microwave studies and the comparison needed before generalization.

Study	Gold-bearing system	Reported focus	Critical limitation to test
Amankwah & Ofori-Sarpong (2011)	Free-milling gold ore	Crack formation, grindability and faster cyanidation	Not inherently representative of refractory ores
Amankwah & Ofori-Sarpong (2020)	Pyrite–arsenopyrite–carbon concentrate	Microwave roasting and oxidation	Off-gas capture and matched-temperature control
Cho et al. (2020a; 2020b)	Refractory gold concentrates	Microwave leaching / nitric-acid-assisted liberation	Lixiviant contribution and full mass balance
Hapid et al. (2024).	Refractory sulfide-bearing gold feed	Microwave roast variable screening	Energy measured at wall; reproducibility
Li et al. (2020; 2021)	Gold-containing cyanide tailings	Thermal treatment and phase response	Residue-specific composition
Wu et al. (2025).	Carlin-type gold ore	Citric-acid-assisted microwave roasting	Additive and irradiation effects separated

Note. Qualitative summaries refer to the study designs, not pooled or benchmarked recovery values. Adapted as a cross-study appraisal from the cited primary literature.

The tabulated studies differ in feed characteristics, analytical endpoints, and leaching conditions. Their results therefore cannot be pooled into a universal recovery factor or transferred uncritically between ore types.

7.2. Negative results and attribution

A refractory ore that already contains fine accessible gold but suffers severe preg-robbing can show little gain from cracking alone. Likewise, refractory samples with poorly coupled gangue can require energy-intensive bulk heating. A neutral or negative outcome is scientifically important, especially when treatment induces passivation or increases reagent consumption (Asamoah, 2021; Cindy et al., 2021; Piervandi, 2023; Wang et al., 2025; Wu, 2023).

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

8. Hybrid Microwave Processing Strategies

8.1. Microwave–roasting and selective oxidants

Microwave-assisted roasting can combine sulfide heating with gas-phase oxidation, while chemical additives may alter surface reaction pathways and apparent efficiency. Design-of-experiments studies help identify interactions among power, exposure, sulfur emissions, and metallurgical performance, yet optimization based solely on gold recovery risks obscuring excess electricity, oxidant consumption, and gas treatment (Hapid et al., 2026; Hapid et al., 2024a; Hapid et al., 2024b; Hapid et al., 2024c; Wu et al., 2025).

8.2. Pressure, atmospheric, and biological oxidation

Pressure oxidation, atmospheric chemical oxidation, and bio-oxidation remain relevant alternative or downstream stages. Microwave pretreatment might shorten subsequent oxidation residence time or reduce grinding demand; these synergies remain hypotheses unless controlled side-by-side studies report the energy and reagent costs of both stages. Biological processing also places constraints on temperature, acidity, and soluble arsenic load (Ahtiainen et al., 2021; Barbouchi et al., 2025a; Barbouchi et al., 2024a; Barbouchi et al., 2024b; Barbouchi et al., 2025b; Boduen et al., 2023; Huang & Yang, 2021; Karimi Darvanjooghi et al., 2024; Zhang et al., 2016; Zhang et al., 2022a).

8.3. Coupling with ultrafine grinding and mechanical activation

Grindability benefits should be tested against high-pressure grinding rolls, stirred-media milling, and mechanical activation at equivalent final liberation. Where ultrafine grinding already achieves sufficient Au exposure, a microwave step may be redundant. Iron-ore, cassiterite, and mechanochemical studies offer methods to test these questions but do not provide direct evidence for gold (Adewuyi et al., 2024; He et al., 2021; Kato et al., 2022; Pereira, 2026c; Tian et al., 2024).

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

Figure 3 positions microwave treatment as an optional process module rather than a universally required upstream step. Its placement depends on whether the ore responds primarily through cracking, oxidation, carbon alteration, or a combination.

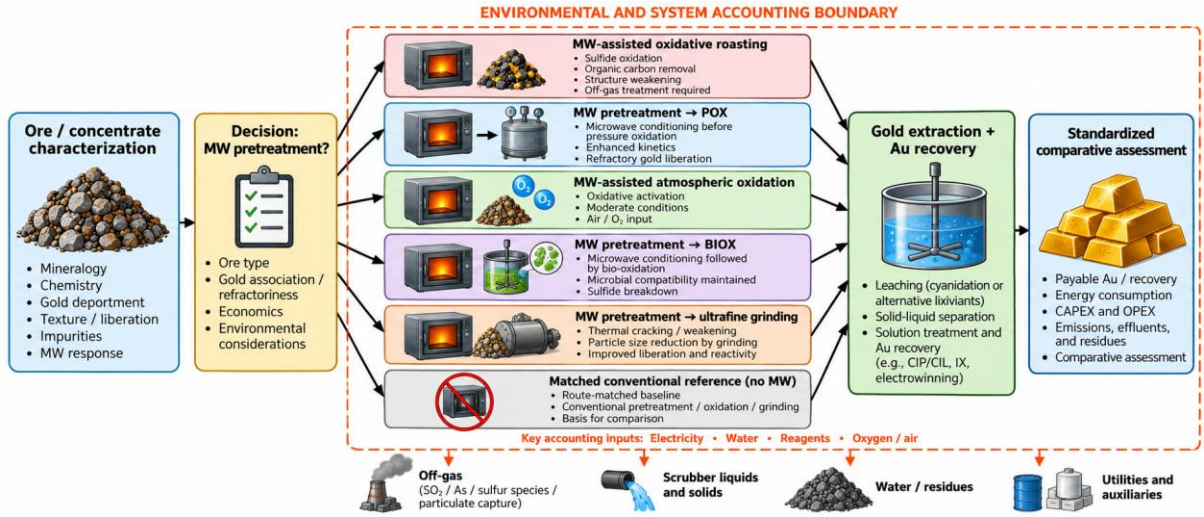


Figure 3. Alternative hybrid microwave pretreatment flowsheets and environmental-control boundary.
Note. Author-developed integration framework adapted from Batchelor et al. (2017), Buttress et al. (2017), and Hapid et al. (2024).

Table 4 summarizes the relevant evidence dimensions and makes explicit the principal limitations for comparing microwave and conventional processing.

Table 4. Comparison of hybrid and reference oxidative routes.

Route	Expected advantage	Critical constraint
Microwave + conventional roasting	Localized preheating or shorter thermal exposure	Duplicated equipment and As/S control
Microwave + POX	Potential shorter reaction time	Pilot-level evidence and capital intensity
Microwave + atmospheric oxidation	Potential increase in reactive area	Large oxidant or acid consumption
Microwave + bio-oxidation	More accessible sulfide surface	Toxicity, pH and heat removal
Microwave + ultrafine grinding	Potential energy and liberation synergy	Net milling savings must exceed microwave input
Conventional POX/bio-oxidation (baseline)	Established reference routes	Comparable feed, target recovery and residues required

Note. Conceptual route comparison rather than demonstrated universal rankings; adapted from Ahtiainen et al. (2021), Boduen et al. (2023), and Barbouchi et al. (2025).

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

None of these hybrid options should be preferred on a presumed microwave advantage alone. Any proposed combination must demonstrate an incremental benefit relative to the complete conventional route.

9. Microwave-Assisted Non-Cyanide Gold Extraction

9.1. Thiourea, thiosulfate, glycine, and chloride

The scope of microwave technology includes preheating followed by alternative lixiviants and irradiation during reactive leaching. Thiourea chemistry, thiosulfate systems, glycine-based extraction, and chloride leaching each impose specific oxidation–reduction, ligand-stability, solution-speciation, and materials-of-construction constraints; enhanced heating does not eliminate these constraints (Ahtiainen et al., 2021; Choi et al., 2017; Li et al., 2022a; Wang et al., 2019a; Wang et al., 2025).

For any non-cyanide claim, consider recovery of dissolved gold into a saleable product alongside lixiviant stability, consumption and recycling, impurity dissolution, solution handling, and the true source of heating efficiency. Do not attribute selectivity and chemical kinetics to microwaves when temperature and leachant chemistry change simultaneously (Cho et al., 2020a; Hapid et al., 2026; Piervandi, 2023).

10. Process Variables and Optimization

10.1. Factorial design and meaningful operating variables

Continuous-reactor validation should report actual dry-feed throughput, measured residence-time distribution (RTD), on-stream availability, feed-property variability, recovered-product variability, field/coupling stability, and wall-plug demand. Check electromagnetic–thermal models against reflected power/S-parameters, measured heating histories, spatial temperature patterns, absorbed-energy estimates, and observed fracture or metallurgical response. Published large-capacity nongold ore systems provide an engineering analog, not direct refractory-gold recovery performance.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

Frequency, applicator geometry, polarization, field strength, electrical input, power coupling, irradiation time, charge mass, bed depth, feed moisture, atmosphere, thermal cycling, and particle size interact. A factorial or response-surface design can quantify technical interactions but should avoid confusing magnetron-rated power with absorbed specific energy. Randomized treatment order and replicates help separate material heterogeneity from process factors (Gutiérrez-Cano et al., 2022; Hapid et al., 2024b; Hapid et al., 2024c; Lin et al., 2022; Ma et al., 2024; Shadi et al., 2023).

Two essential measurements are net wall-plug specific energy (kWh per tonne of feed treated) and incremental energy per additional gram of recovered gold. The latter requires a valid comparison with untreated or conventionally treated samples and a fixed downstream endpoint.

A hierarchy of responses is recommended: input mineralogy and coupling, actual thermal trajectory, phase changes, microcrack/liberation response, leaching extraction and reagent use, and integrated energy/economic performance. Report replicate ore splits, uncertainty ranges, and mass-balance closure, especially for samples with heterogeneous sulfide assemblages (Barbouchi et al., 2026; Hamchi et al., 2026a; Li et al., 2022a; Ma et al., 2023).

For equivalent throughput, product quality, and saleable-gold accounting boundaries, incremental electricity per incremental recovered gold is $E_{\Delta Au} = (E_{MW, system} - E_{reference, system})/(m_{Au, saleable, MW} - m_{Au, saleable, reference})$. This incremental ratio is undefined when the recovery difference is zero, and its sign is potentially misleading if recovery decreases; in such cases, report energy and recovery changes separately. A full technical-economic assessment must separately attribute throughput, comminution, oxidation, leaching time, and recovery effects while including generator, applicator, shielding, feeder, gas-treatment, and downstream CAPEX, electricity, consumables, maintenance, availability, and waste costs.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

Specific whole-system energy is E_wall = [∫ P_wall(t) dt] / m_feed. Where ports and calibrations permit, E_abs,net = [∫ (P_forward(t) − P_reflected(t) − P_transmitted(t)) dt − E_applicator_losses] / m_feed; omitting applicator losses measures net power entering the load region, not necessarily energy absorbed by the sample. All powers should be measured or their estimation disclosed. System totals include generator inefficiency, feeding, cooling, extraction/ventilation, emissions control, and downstream energy at a declared dry-feed basis (e.g., kWh/t).

Figure 4 illustrates why maximum severity is not necessarily optimal: hotter treatment may enhance oxidation but also induce sintering and make neutralization more difficult.

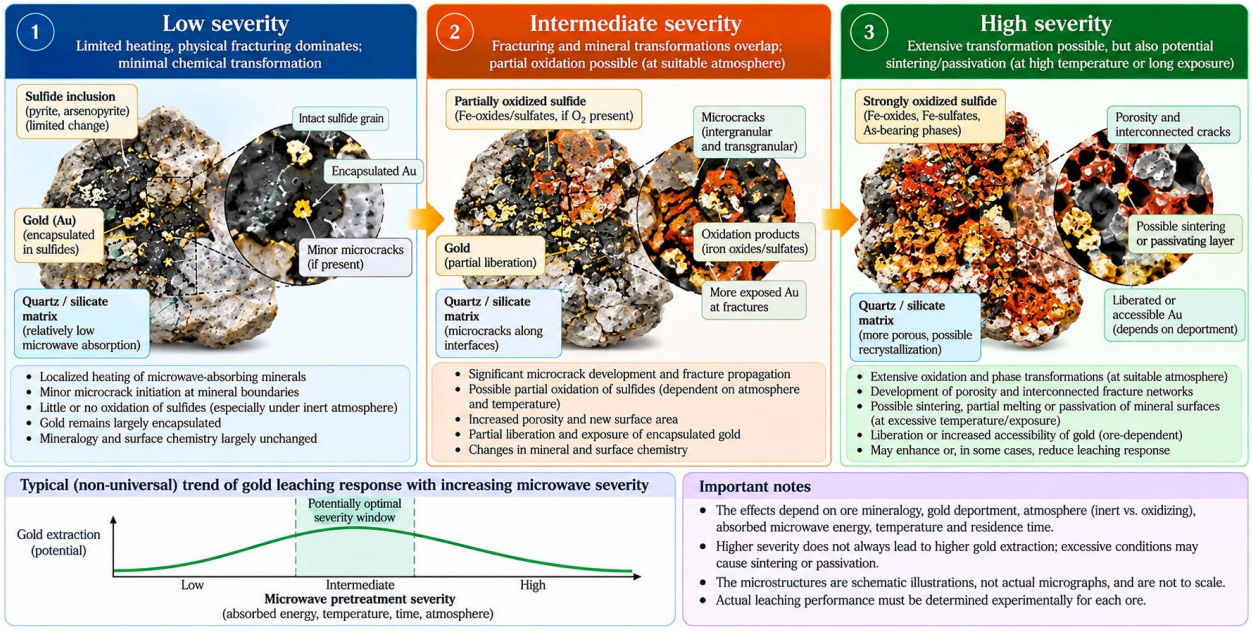


Figure 4. Conceptual progression of mechanisms with increasing treatment severity.
Note. Author-developed qualitative conceptualization adapted from Hapid et al. (2024), Li et al. (2022), and Zhang et al. (2021); axes are intentionally nonnumeric.

11. Scale-Up, Energy Efficiency, and Techno-Economics

11.1. Reactor design and continuous operation

Continuous systems must maintain throughput and reproducible field distributions as feed moisture, composition, and particle-size distribution change. At scale, microwave

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

penetration, applicator coupling, moving-bed mixing, dielectric temperature feedback, dust management, and shielding become decisive. Reports of large-scale microwave ore-treatment platforms demonstrate engineering feasibility for comminution-related applications, not automatic feasibility for gold-bearing oxidative pretreatment (Batchelor et al., 2017; Buttress et al., 2017; Pressacco et al., 2022; Pressacco et al., 2023; Rasyid et al., 2023).

Thermal and electromagnetically coupled numerical models can provide useful geometry and energy-distribution diagnostics, but need validation against measured temperatures, reflected power, breakage, and process performance. Rock fracture and ore sorting technology should be cited as engineering analogs, not as direct gold recovery demonstrations (Ahmadihosseini et al., 2025; Ahmadihosseini et al., 2022; Kafashi et al., 2025; Liang et al., 2023; Tian et al., 2024; Xu et al., 2021a).

Table 5 summarizes the relevant evidence dimensions and makes explicit the principal limitations for comparing microwave and conventional processing.

Table 5. Evidence ladder for scale-up and industrial readiness.

Evidence tier	Required demonstration	Common gap
Material screening	Mineralogy, dielectric and thermal response	Selected favorable specimen
Paired bench tests	Microwave versus temperature-matched baseline	Absent electrical metering
Integrated bench flowsheet	Recovery, reagent, solid and gas balances	Only gold dissolution reported
Continuous pilot	Throughput, uptime, residence time and control	Batch-to-scale extrapolation
Industrial decision	Sensitivity to ore variability and net present value	No comparable conventional reference

Note. Proposed review-specific assessment framework informed by Batchelor et al. (2017), Buttress et al. (2017), and Tian et al. (2024).

Progression between evidence tiers requires reproducible results and explicit decision criteria. Evidence from non-gold continuous systems cannot by itself validate gold-processing performance.

Table 6 summarizes the relevant evidence dimensions and makes explicit the principal limitations for comparing microwave and conventional processing.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

Table 6. Boundary conditions for a fair energy, environmental, and economic comparison.

Metric	Microwave route	Conventional comparator	Decision rule
Energy	Wall-plug kWh/t plus auxiliaries	Fuel and electricity at equivalent scope	Net energy by equal recovery target
Gold recovery	Au recovered, kinetics and product	Matched leaching chemistry and grind	Incremental saleable Au
Reagents	Oxidants, CN, lime, wash water	Full reagent and recycle balance	Net operating costs
Air/residues	As, SOx, fines and scrubber residues	Same emissions and waste boundary	Compliance and handling burden
Capital/uptime	Applicator, shielding, maintenance	Established roast, POX or milling	Risk-adjusted project value

Note. Proposed accounting matrix, not empirical quantitative cost benchmarking. All comparisons should use consistent feed properties, product specification, allocation, and system boundaries.

The comparison must use a common mass, time, and product-recovery basis. A decrease in unit energy consumption is not sufficient if gold recovery, emissions, reagent use, or operating availability deteriorate.

12. Critical Synthesis and Selection Framework

12.1. When microwaves merit further testing

Strong justification requires a feed with responsive mineral domains, a measurable mechanism that confers metallurgical advantage, a practicable operating window, and improvement against the best available reference technology. Sulfide-rich concentrates may allow lower mass throughput than whole ore, but concentrate production and residue treatment should be included in the decision boundary. Pre-sorting and selective irradiation may be useful only when their measurement and sorting costs are captured (Barbouchi et al., 2026; Barbouchi et al., 2025b; Chen et al., 2024; Shahbazi, 2026; Tian et al., 2024).

Table 7 provides a decision scorecard, and Figure 5 shows validation. The framework intentionally contains no universal threshold for grade, power, sulfide fraction, or recovery because such thresholds must be determined with ore-specific experiments and local costs.

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

Table 7. Stage-gated selection scorecard for refractory gold microwave pretreatment.

Gate	Evidence to acquire	Proceed only if
1. Diagnosis	Host mineral, Au deportment, preg-robbing, As/S	Targetable refractory mechanism exists
2. Response	Dielectric, thermal, phase and fracture diagnostics	Meaningful controlled response occurs
3. Comparator	Matched-temperature heating, grinding, POX/bio-oxidation	Incremental process advantage survives
4. Integration	Au recovery, reagents, off-gas, water, residues	Technically sound integrated flowsheet
5. Scale and value	Continuous pilot, capital and sensitivity model	Positive risk-adjusted net value

Note. Author-proposed framework synthesized from the preceding sections; no source claims a universal cutoff.

The scorecard is a decision aid rather than a calibrated predictive model. Site-specific thresholds should be supported by uncertainty analysis and confirmatory pilot data.

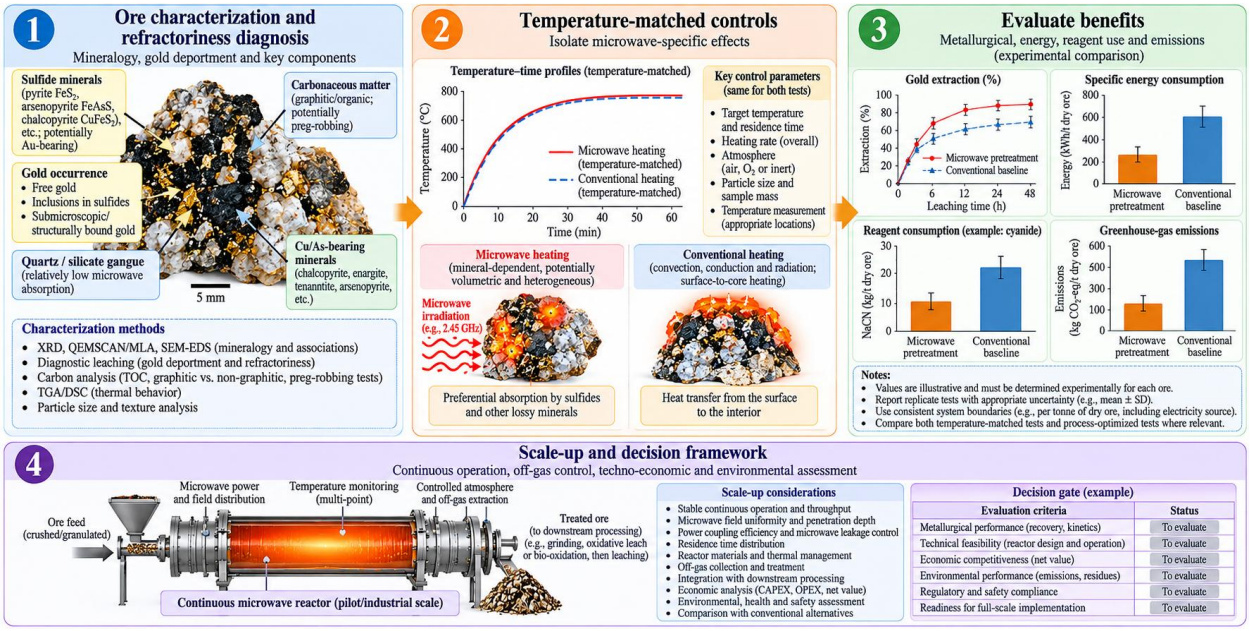


Figure 5. Stage-gated decision framework for microwave implementation in gold-processing flowsheets.
Note. This review constructed the original conceptual framework, informed by the assessment domains of Batchelor et al. (2017), Tian et al. (2024), and Shahbazi (2026).

Other studies used only as methodological context—rather than direct evidence for improved refractory-gold recovery—address mineral response, conventional roasting, comparative leaching, and rock fragmentation (Rogozhnikov et al., 2019; Xiao et al., 2026;

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

Zhu et al., 2018). These papers motivate experimental control design rather than establish recoveries transferable to refractory gold feeds.

13. Conclusions and Future Perspectives

Microwave processing is a potentially valuable, but intrinsically feed-dependent, pretreatment technology. Its distinctive opportunity lies in differential electromagnetic energy absorption and the resulting interplay of fractures, mineral reactions, and changing gold accessibility. A reported recovery improvement alone does not establish a microwave-specific mechanism, much less a favorable plant-scale energy balance. The most compelling applications are those that can demonstrate a repeatable benefit using ore-representative samples and rigorous conventional-treatment controls.

Future investigations should use matched thermal histories, measured wall-plug energy, quantified absorbed power, and joint mineralogical–hydrometallurgical diagnostics. Continuous testing must demonstrate controlled residence-time distribution, reliable product quality, credible arsenic–sulfur management, and robustness to feed variability. Technology selection should then be based on comparable life-cycle and project-economic boundaries rather than isolated recovery maxima.

Declarations

Funding: To be confirmed by the corresponding author before submission.

Conflicts of interest: The author must provide a complete journal-specific disclosure, including relevant consulting relationships.

Data availability: No new experimental dataset was generated. The supporting studies are identified in the References section.

Ethics approval and consent to participate: Not applicable to this literature review.

Author contributions: To be verified and approved by the author according to the journal's contributor policy.

References

Adewuyi, S. O., Ahmed, H. A. M., & Ahmed, H. M. A. (2020). Methods of ore pretreatment for comminution energy reduction. Minerals, 10(5), 423. https://doi.org/10.3390/min10050423

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

Adewuyi, S. O., Ahmed, H. A. M., Anani, A., Saeed, A., Ahmed, H. M., Alwafi, R., & Luxbacher, K. (2024). Enhancing iron ore grindability through hybrid thermal-mechanical pretreatment. Minerals, 14(10), 1027. https://doi.org/10.3390/min14101027

Ahmadihosseini, A., Aslam, A., Rafiei, A., Hassani, F., & Sasmito, A. (2025). Energy efficiency analysis of microwave treatment in rocks: From mine-to-mill operations. Applied Energy, 386, 125589. https://doi.org/10.1016/j.apenergy.2025.125589

Ahmadihosseini, A., Shadi, A., Rabiei, M., Samea, P., Hassani, F., & Sasmito, A. P. (2022). Computational study of microwave heating for rock fragmentation: model development and validation. International Journal of Thermal Sciences, 181, 107746. https://www.sciencedirect.com/science/article/pii/S1290072922002794

Ahtiainen, R., Liipo, J., & Lundström, M. (2021). Simultaneous sulfide oxidation and gold dissolution by cyanide-free leaching from refractory and double refractory gold concentrates. Minerals Engineering, 170, 107042. https://doi.org/10.1016/j.mineng.2021.107042

Amankwah, R. K., & Ofori-Sarpong, G. (2011). Microwave heating of gold ores for enhanced grindability and cyanide amenability. Minerals Engineering, 24(6), 541–544. https://doi.org/10.1016/j.mineng.2010.12.002

Amankwah, R. K., & Ofori-Sarpong, G. (2020). Microwave roasting of flash flotation concentrate containing pyrite, arsenopyrite and carbonaceous matter. Minerals Engineering, 151, 106312. https://doi.org/10.1016/j.mineng.2020.106312

Asamoah, R. K. (2021). Specific refractory gold flotation and bio-oxidation products: Research overview. Minerals, 11(1), 93. https://doi.org/10.3390/min11010093

Barbouchi, A., Ayadi, S., Idouhli, R., Khadiri, M.-E., Abouelfida, A., Barfoud, L., Faqir, H., Benzakour, I., & Benzakour, J. (2025b). Highly efficient pretreatment for refractory gold ores using persulfate, catalyst and free radical based advanced oxidation processes to improve cyanidation. Hydrometallurgy, 235, 106488. https://doi.org/10.1016/j.hydromet.2025.106488

Barbouchi, A., Dachri, K., Labbilta, T., Naji, K., Faqir, H., Benzakour, I., Idouhli, R., Khadiri, M.-E., Abouelfida, A., & Benzakour, J. (2026). Improving flotation recovery of gold in a refractory gold ore: An integrated approach between response surface methodology and automated quantitative mineralogy. Physicochemical Problems of Mineral Processing, 62(1). https://doi.org/10.37190/ppmp/216390

Barbouchi, A., Er-Raqi, I., Hamchi, M., Idouhli, R., Khadiri, M.-E., Abouelfida, A., El Alaoui-Chrifi, M. A., Faqir, H., Benzakour, I., & Benzakour, J. (2024a). Chemical oxidation of arsenopyrite by strong oxidizing agents: For oxidative pretreatment of refractory arsenopyritic gold ores. Acta Geodynamica et Geomaterialia, 21(3), 185–194. https://doi.org/10.13168/AGG.2024.0017

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

Barbouchi, A., Er-Raqi, I., Idouhli, R., Khadiri, M.-E., Abouelfida, A., Louarrat, M., Mikali, M., El Alaoui-Chrifi, M. A., Faqir, H., Benzakour, I., & Benzakour, J. (2024b). Chemical oxidation of pyrite by strong oxidizing agents: For pretreatment of refractory pyritic gold ores. Acta Montanistica Slovaca, 29(4), 773–786. https://doi.org/10.46544/AMS.v29i4.01

Barbouchi, A., Louarrat, M., Mikali, M., Barfoud, L., El Alaoui-Chrifi, M. A., Faqir, H., Benzakour, I., Idouhli, R., Khadiri, M.-E., & Benzakour, J. (2025a). Advancements in improving gold recovery from refractory gold ores/concentrates: A review. Canadian Metallurgical Quarterly, 64(4), 2370–2387. https://doi.org/10.1080/00084433.2024.2441548

Bare, G. T., Mbayo, J. J. K., Ndlovu, S., Shemi, A., & Chipise, L. (2022). Mineralogical characterization and acid pretreatment of a gold calcine leach residue. Minerals, 12(1), 10. https://doi.org/10.3390/min12010010

Batchelor, A. R., Buttress, A. J., Jones, D. A., Katrib, J., Way, D., Chenje, T., Stoll, D., Dodds, C., & Kingman, S. W. (2017). Towards large scale microwave treatment of ores: Part 2 – Metallurgical testing. Minerals Engineering, 111, 5–24. https://doi.org/10.1016/j.mineng.2017.05.003

Boduen, A., Zalesov, M., Melamud, V., Grigorieva, V., & Bulaev, A. (2023). Combined bacterial and pressure oxidation for processing high-sulfur refractory gold concentrate. Processes, 11(11), 3062. https://doi.org/10.3390/pr11113062

Buttress, A. J., Katrib, J., Jones, D. A., Batchelor, A. R., Craig, D. A., Royal, T. A., Dodds, C., & Kingman, S. W. (2017). Towards large scale microwave treatment of ores: Part 1 – Basis of design, construction and commissioning. Minerals Engineering, 109, 169–183. https://doi.org/10.1016/j.mineng.2017.03.006

Chai, X., Liu, R., Dong, W., Sun, W., & Lin, S. (2025). Surface physicochemical property differences between gold-bearing and gold-free pyrite for efficient and clean processing of refractory pyritic gold ores. Minerals, 15(6), 577. https://doi.org/10.3390/min15060577

Chen, J., Li, X., Gao, L., Guo, S., & He, F. (2024). Microwave treatment of minerals and ores: Heating behaviors, applications, and future directions. Minerals, 14(3), 219. https://doi.org/10.3390/min14030219

Cho, K., Kim, H., Myung, E., Purev, O., Choi, N., & Park, C. (2020b). Recovery of gold from the refractory gold concentrate using microwave assisted leaching. Metals, 10(5), 571. https://doi.org/10.3390/met10050571

Cho, K., Lee, J. J., & Park, C. Y. (2020a). Liberation of gold using microwave-nitric acid leaching and separation-recovery of native gold by hydro-separation. Minerals, 10(4), 327. https://doi.org/10.3390/min10040327

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

Choi, N.-C., Kim, B.-J., Cho, K., Lee, I. D. S., & Park, C.-Y. (2017). Microwave pretreatment for thiourea leaching for gold concentrate. Metals, 7(10), 404. https://doi.org/10.3390/met7100404

Cindy, Sakai, R., Mendoza, D. M., Konadu, K. T., & Sasaki, K. (2021). Significance of acid washing after biooxidation of sulfides in sequential biotreatment of double refractory gold ore from the Syama Mine, Mali. Minerals, 11(12), 1316. https://doi.org/10.3390/min11121316

Diaz, M., Amaya, I., & Correa-Cely, R. (2016). Microwave enhanced roasting for pyrite ore samples with dielectric properties strongly dependent on temperature. Ingeniería y Universidad, 20(1), 63–84. https://doi.org/10.11144/Javeriana.iyu20-1.merp

Espinoza-Martínez, A. M., Valenzuela-García, J. L., Salazar-Campoy, M. M., Encinas-Romero, M. A., Martínez-Ballesteros, G., & Parga Torres, J. R. (2025). Gold and silver recovery from a refractory pyritic concentrate by roasting and alkaline pressure oxidation. Minerals, 15(12), 1260. https://doi.org/10.3390/min15121260

Guner, M. K., Bulut, G., Hassanzadeh, A., Lode, S., & Aasly, K. (2023). Automated mineralogy and diagnostic leaching studies on bulk sulfide flotation concentrate of a refractory gold ore. Minerals, 13(10), 1243. https://doi.org/10.3390/min13101243

Gutiérrez-Cano, J. D., Catalá-Civera, J. M., López-Buendía, A. M., Plaza-González, P. J., & Penaranda-Foix, F. L. (2022). High-resolution detection of rock-forming minerals by permittivity measurements with a near-field scanning microwave microscope. Sensors, 22(3), 1138. https://doi.org/10.3390/s22031138

Hamchi, M., Barbouchi, A., Idouhli, R., Mabsout, M., Ait Bouazza, M., Abouelfida, A., & Khadiri, M.-E. (2026a). Comparative evaluation of gravity–CIL and flotation–pretreatment–CIL routes for the recovery of gold from refractory sulphide ore. Mining, Metallurgy & Exploration, 43(2), 1511–1521. https://doi.org/10.1007/s42461-026-01501-7

Hamchi, M., Barbouchi, A., Idouhli, R., Mabsout, M., Ait Bouazza, M., Botes, W., Mutshidzi, S., Abouelfida, A., & Khadiri, M.-E. (2026b). Hyperoxygenation and fine grinding enhance carbon-in-leach recovery of refractory gold: Lab-to-pilot validation using the Aachen reactor. Canadian Metallurgical Quarterly. https://doi.org/10.1080/00084433.2025.2611504

Hao, J., Li, Q., & Qiao, L. (2021). Study on magnetite ore crushing assisted by microwave irradiation. Minerals, 11(10), 1127. https://doi.org/10.3390/min11101127

Hapid, A., Kawigraha, A., Permatasari, N. V., Ikhwani, N., Zullaikah, S., Mahfud, M., & Assabumrungrat, S. (2026). Synergistic microwave-assisted roasting and leaching to enhance gold extraction from refractory gold ore using an environmentally friendly deep eutectic solvent. Journal of Sustainable Metallurgy, 12(2), 1715–1735. https://doi.org/10.1007/s40831-025-01405-8

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

Hapid, A., Zullaikah, S., Mahfud, Kawigraha, A., Sudiyanto, Y., Nareswari, R. B., & Quitain, A. T. (2024c). Oxidation of sulfide mineral and metal extraction analysis in the microwave-assisted roasting pretreatment of refractory gold ore. Arabian Journal of Chemistry, 17, 105447. https://doi.org/10.1016/j.arabjc.2023.105447

Hapid, A., Zullaikah, S., Mahfud, M., & Kawigraha, A. (2024a). Effect of power and exposure time on the microwave-assisted roasting of refractory gold ore. Materials Science Forum, 1113, 111–117. https://doi.org/10.4028/p-L8NrjW

Hapid, A., Zullaikah, S., Mahfud, M., Kawigraha, A., Azmi, M. U., Haryanto, I., Soewoto, H. P., Go, A. W., & Assabumrungrat, S. (2024b). Optimization of microwave-assisted roasting: Box-Behnken design for oxidation of sulfide minerals and control of atmospheric sulfur in refractory gold ore pretreatment. Case Studies in Chemical and Environmental Engineering, 10, 100826. https://doi.org/10.1016/j.cscee.2024.100826

He, C., Zhao, J., Su, X., Ma, S., Fujita, T., Wei, Y., Yang, J., & Wei, Z. (2021). Thermally assisted grinding of cassiterite associated with pollimetallic ore: A comparison between microwave and conventional furnaces. Minerals, 11(7), 768. https://doi.org/10.3390/min11070768

Huang, Z.-S., & Yang, T.-Z. (2021). Comparative study on refractory gold concentrate kinetics and mechanisms by pilot scale batch and continuous bio-oxidation. Minerals, 11(12), 1343. https://doi.org/10.3390/min11121343

Jaansalu, M., & Pickles, C. (2025). Comparison of ferronickel alloys produced via microwave and conventional thermal concentration of pyrrhotite tailings. Minerals, 15(3), 196. https://doi.org/10.3390/min15030196

Jiménez Tovar, G. A., Torres Gómez, R., Parra Pinilla, M., Córdoba Angarita, O., Sosa, D., & Ortíz, C. (2022). Microwave treatment for gold minerals used in small-scale mining. Journal of Applied Research and Technology, 20(4), 399–407. https://doi.org/10.22201/icat.24486736e.2022.20.4.1771

Jin, J., Han, Y., Li, H., Huai, Y., Peng, Y., Gu, X., & Yang, W. (2019). Mineral phase and structure changes during roasting of fine-grained carbonaceous gold ores and their effects on gold leaching efficiency. Chinese Journal of Chemical Engineering, 27(5), 1184–1190. https://doi.org/10.1016/j.cjche.2018.08.006

Kafashi, S., Esteban, L., Bona, A., & Nikoloski, A. N. (2025). Microwave-induced fracturing for enhanced permeability in hard rocks: A novel approach for in situ recovery in mining. Minerals, 15(11), 1210. https://doi.org/10.3390/min15111210

Karimi Darvanjooghi, M. H., Magdouli, S., & Brar, S. K. (2024). Recent challenges in biological cyanidation and oxidation of sulfide-based refractory gold ore. World Journal of Microbiology and Biotechnology, 40(2), 67. https://doi.org/10.1007/s11274-024-03887-2

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

Kato, T., Iwamoto, M., & Tokoro, C. (2022). Investigation of cerium reduction efficiency by grinding with microwave irradiation in mechanochemical processing. Minerals, 12(2), 189. https://doi.org/10.3390/min12020189

Konadu, K. T., Mendoza, D. M., Huddy, R. J., Harrison, S. T. L., Kaneta, T., & Sasaki, K. (2020). Biological pretreatment of carbonaceous matter in double refractory gold ores: A review and some future considerations. Hydrometallurgy, 196, 105434. https://doi.org/10.1016/j.hydromet.2020.105434

Li, H., Li, Z., Jin, J., Han, Y., & Li, Y. (2022b). Pore evolution in refractory gold ore formed by oxidation roasting and the effect on the cyanide leaching process. ACS Omega, 7(4), 3618–3625. https://doi.org/10.1021/acsomega.1c06248

Li, H., Long, H., Zhang, L., Yin, S., Li, S., Zhu, F., & Xie, H. (2020). Effectiveness of microwave-assisted thermal treatment in the extraction of gold in cyanide tailings. Journal of Hazardous Materials, 384, 121456. https://doi.org/10.1016/j.jhazmat.2019.121456

Li, H., Oraby, E., Eksteen, J., & Mali, T. (2022a). Extraction of gold and copper from flotation tailings using glycine-ammonia solutions in the presence of permanganate. Minerals, 12(5), 612. https://doi.org/10.3390/min12050612

Li, H., Peng, J., Ma, P., Zhou, Z., Long, H., Li, S., & Zhang, L. (2021a). Application of diagnostic roasting method in thermochemical treatment for Au recovery from gold-containing tailings in microwave field. Minerals Engineering, 163, 106773. https://doi.org/10.1016/j.mineng.2021.106773

Li, H., Xiao, W., Jin, J., & Han, Y. (2021c). Oxidation roasting of fine-grained carbonaceous gold ore: The effect of aeration rate. Minerals, 11(6), 558. https://doi.org/10.3390/min11060558

Li, Q., Li, X., & Yin, T. (2021b). Effect of microwave heating on fracture behavior of granite: An experimental investigation. Engineering Fracture Mechanics, 250, 107758. https://doi.org/10.1016/j.engfracmech.2021.107758

Liang, C.-G., Guo, Z.-S., Yue, X., Li, H., & Ma, P.-C. (2023). Microwave-assisted breakage of basalt: A viewpoint on analyzing the thermal and mechanical behavior of rock. Energy, 273, 127225. https://doi.org/10.1016/j.energy.2023.127225

Lin, F., Feng, X.-T., Li, S.-P., Zhang, J.-Y., Su, X.-X., & Tong, T.-Y. (2023). Effects of particle size and morphology on microwave cracking characteristics and cracking mechanism of three Fe-containing ores. Geomechanics and Geophysics for Geo-Energy and Geo-Resources, 9, 100. https://doi.org/10.1007/s40948-023-00626-z

Lin, F., Feng, X.-T., Yang, C., Li, S., Zhang, J., Su, X., & Tong, T. (2022). Microwave response characteristics and influencing factors of ores based on dielectric properties

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

of synthetic samples. Journal of Rock Mechanics and Geotechnical Engineering, 14(2), 315–328. https://doi.org/10.1016/j.jrmge.2021.08.002

Lin, S., Gao, L., Yang, Y., Chen, J., Guo, S., Omran, M., & Chen, G. (2020). Dielectric properties and high temperature thermochemical properties of the pyrolusite-pyrite mixture during reduction roasting. Journal of Materials Research and Technology, 9(6), 13128–13136. https://doi.org/10.1016/j.jmrt.2020.09.056

Lu, G., Zhou, J., Li, Y., Zhang, X., & Gao, W. (2020). The influence of minerals on the mechanism of microwave-induced fracturing of rocks. Journal of Applied Geophysics, 180, 104123. https://doi.org/10.1016/j.jappgeo.2020.104123

Ma, L., Liu, X., Wang, L., & Qi, J. (2023). Mineral phase evolution during oxidation roasting pretreatment of typical Carlin gold ore and effects on gold leaching efficiency. Minerals, 13(4), 558. https://doi.org/10.3390/min13040558

Ma, S. J., Luo, W. J., Mo, W., Su, X. J., Liu, P., & Yang, J. L. (2010). Removal of arsenic and sulfur from a refractory gold concentrate by microwave heating. Minerals Engineering, 23(1), 61–63. https://www.sciencedirect.com/science/article/pii/S089268750900243X

Ma, Z., Zheng, Y., Li, J., Zhao, X., & Zhao, J. (2024). Enhancing rock breakage efficiency by microwave fracturing: A study on antenna selection. Energy, 288, 129876. https://doi.org/10.1016/j.energy.2023.129876

Mao, Y., Ying, H., Yang, Y., Liu, M., & Li, X. (2026). Influence of oxidation roasting on pore structure evolution and gold extraction in refractory gold concentrate. Minerals, 16(9), 902. https://doi.org/10.3390/min16090902

Matar, M., Lim, B., Albijanic, B., Oraby, E., Baawuah, E., Staunton, W., & Blackwell, K. (2026). Industrial relevance of oxidants and leaching accelerants in cyanidation of gold sulfide ores. Minerals, 16(7), 745. https://doi.org/10.3390/min16070745

Mutimutema, P., Akdogan, G., & Tadie, M. (2022). Evaluation of pre-treatment methods for gold recovery from refractory calcine tailings. Journal of the Southern African Institute of Mining and Metallurgy, 122(10), 561–570. https://doi.org/10.17159/2411-9717/2070/2022

Navas Jaramillo, S. J., & Gonzalez Zuñiga, R. E. (2025). Characteristics of mineralization of refractory gold and its influence on cyanide gold leaching rates: A case study in Pituca II, Zamora Chinchipe, Ecuador. Minerals, 15(5), 523. https://doi.org/10.3390/min15050523

Okibe, N., Hayashi, K., Oyama, K., Shimada, K., Aoki, Y., Suwa, T., & Hirajima, T. (2022). Bioleaching of enargite/pyrite-rich “dirty” concentrate and arsenic immobilization. Minerals, 12(4), 449. https://doi.org/10.3390/min12040449

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

Pereira, A. C. (2025). Refractory gold ores: A critical review of mineralogy and processing options. Revista FT, 29(153), 1–39. https://doi.org/10.69849/revistaft/ra10202512141446

Pereira, A. C. (2026a). Disposal, stabilization, and conditional valorization of arsenic-bearing wastes generated in hydrometallurgical processes: A critical review. Nexus Science Review, 1(5). https://doi.org/10.66104/ry2vm015

Pereira, A. C. (2026b). Gold cyanidation behavior of limonitic ores from the Carajás Province, Brazil: Mineralogical controls, cyanide consumption, and leaching kinetics. International Journal of Research and Innovation in Social Science, 10(6), 6755–6776. https://doi.org/10.47772/IJRISS.2026.100600467

Pereira, A. C. (2026c). Mechanical activation in metallurgical processing: Mechanisms, applications and industrial perspectives. IKR Journal of Engineering and Technology, 2, 1–34. https://doi.org/10.5281/zenodo.18912251

Pereira, A. C. (2026d). Preg-robbing in refractory gold ores: A critical review of mineralogical controls, pretreatment strategies and flowsheet selection. International Journal of Current Science Research and Review, 9(4), 1672–1704. https://doi.org/10.47191/ijcsrr/V9-i4-02

Pereira, A. C. (2026e). Refractory Gold Ores Associated with Silicate Matrices: Mineralogical Controls, Pretreatment Technologies, Alternative Leaching Systems, and Flowsheet Optimization. NEXUS SCIENTIFIC JOURNAL (NSJ), 1(6), 1–38. https://doi.org/10.5281/zenodo.23251282

Pereira, A. C. (2026f). Sequential acid–cyanide diagnostic leaching to quantify cyanide-soluble copper in a gold-bearing oxidized copper ore. IKR Journal of Engineering and Technology, 2(5), 1–12. https://doi.org/10.5281/zenodo.22286399

Pereira, A. C., Barbosa, V. da S. B., & Rodrigues, M. L. M. (2017). Effectiveness of acidic pre-cleaning for copper-gold ore. REM - International Engineering Journal, 70(4), 445–450. https://doi.org/10.1590/0370-44672016700126

Pereira, A. C., Gomes, M. R. dos S., & Manfridini, A. P. de A. (2018). Ensaios exploratórios de lixiviação de ouro associado a minérios limoníticos. Brazilian Applied Science Review, 3(2), 1010–1022. https://doi.org/10.34115/basr.v3i2.998

Pickles, C. A., & Lu, T. (2022). Microwave dewatering of gibbsite-type bauxite ores: Permittivities, heating behavior and strength indices. Minerals, 12(5), 648. https://doi.org/10.3390/min12050648

Piervandi, Z. (2023). Pretreatment of refractory gold minerals by ozonation before the cyanidation process: A review. Journal of Environmental Chemical Engineering, 11(1), 109013. https://doi.org/10.1016/j.jece.2022.109013

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

Pressacco, M., Kangas, J. J. J., & Saksala, T. (2022). Numerical modelling of microwave heating assisted rock fracture. Rock Mechanics and Rock Engineering, 55, 481–503. https://doi.org/10.1007/s00603-021-02685-8

Pressacco, M., Kangas, J. J. J., & Saksala, T. (2023). Numerical modelling of microwave irradiated rock fracture. Minerals Engineering, 203, 108318. https://doi.org/10.1016/j.mineng.2023.108318

Qin, H., Guo, X., Tian, Q., Yu, D., & Zhang, L. (2021). Recovery of gold from sulfide refractory gold ore: Oxidation roasting pretreatment and gold extraction. Minerals Engineering, 164, 106822. https://doi.org/10.1016/j.mineng.2021.106822

Rasyid, M. A., Aslam, A., Rafiei, A., Hassani, F., & Sasmito, A. P. (2023). Application of instantaneous power draw analysis to investigate the impact of microwave heating on kimberlite ore crushing. Applied Energy, 352, 121900. https://doi.org/10.1016/j.apenergy.2023.121900

Rogozhnikov, D. A., Shoppert, A. A., Dizer, O. A., Karimov, K. A., & Rusalev, R. E. (2019). Leaching kinetics of sulfides from refractory gold concentrates by nitric acid. Metals, 9(4), 465. https://doi.org/10.3390/met9040465

Sapinov, R., Shoshay, Z., Sadenova, M., & Kassymova, D. (2026). Processing of technogenic gold-bearing raw materials using preliminary energy-efficient microwave treatment. Engineering, Technology & Applied Science Research, 16(1), 31571–31578. https://doi.org/10.48084/etasr.15638

Seflek, C., & Bayat, O. (2018). Microwave-assisted grinding of Bolkardag (Nigde, Turkey) gold ore and enhanced cyanide leachability. Metallurgical Research & Technology, 115(5), 508. https://doi.org/10.1051/metal/2018039

Shadi, A., Samea, P., Rabiei, M., & Ghoreishi-Madiseh, S. A. (2023). Energy efficiency of microwave-induced heating of crushed rocks/ores. Minerals, 13(7), 924. https://doi.org/10.3390/min13070924

Shahbazi, B. (2026). Microwave-assisted technologies in gold extraction: A review. Engineering Reports, 8(1), e70579. https://doi.org/10.1002/eng2.70579

Shi, J., Song, Y., Zhang, X., Yin, N., Wang, Z., Lang, S., Wang, Y., & Zhu, B. (2025). Effect of roasting temperature in the synergistic roasting process of carbonaceous gold ore and cyanide tailings. Minerals Engineering, 233, 109636. https://doi.org/10.1016/j.mineng.2025.109636

Tian, X., Forster, J., & Bobicki, E. R. (2024). Technological and economic considerations for the application of combined microwave-assisted comminution and multi-sensor ore sorting. Minerals Engineering, 208, 108582. https://doi.org/10.1016/j.mineng.2024.108582

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

Wang, H., Feng, Y., Li, H., & Kang, J. (2019b). The separation of gold and vanadium in carbonaceous gold ore by one-step roasting method. Powder Technology, 355, 191–200. https://doi.org/10.1016/j.powtec.2019.07.037

Wang, J., Wang, W., Dong, K., Fu, Y., & Xie, F. (2019a). Research on leaching of carbonaceous gold ore with copper-ammonia-thiosulfate solutions. Minerals Engineering, 137, 232–240. https://doi.org/10.1016/j.mineng.2019.04.013

Wang, P., Yin, T., Li, X., & Konietzky, H. (2023). Quasi-static and dynamic tensile behavior of water-bearing sandstone subjected to microwave irradiation. Mathematics, 11(1), 203. https://doi.org/10.3390/math11010203

Wang, S., Wu, J., & Jiao, F. (2025). Pretreatment and extraction of gold from refractory gold ore in acidic conditions. Minerals, 15(4), 340. https://doi.org/10.3390/min15040340

Wang, S., Xu, Y., Xia, K., & Tong, T. (2021). Dynamic fragmentation of microwave irradiated rock. Journal of Rock Mechanics and Geotechnical Engineering, 13(2), 300–310. https://doi.org/10.1016/j.jrmge.2020.09.003

Wu, T., Shen, Z., Shi, Z., Wang, J., Qiu, Y., & Mao, S. (2025). Enhancement of gold extraction by citric acid-assisted microwave roasting of Carlin-type gold ores and sulfide/thiosulfate leaching. Hydrometallurgy, 231, 106410. https://www.sciencedirect.com/science/article/pii/S0304386X24001506

Wu, W. (2023). Current status and progress in the research of gold ore treatment processes. Gold, 44(1), 42–48. https://doi.org/10.11792/hj20230109

Xiao, H., Jin, J., He, F., Han, Y., & Sun, Y. (2022b). Strengthening gold extraction from carbonaceous gold ore based on decarburization by two-stage fluidized oxidation roasting. Minerals, 12(12), 1620. https://doi.org/10.3390/min12121620

Xiao, H., Jin, J., He, F., Han, Y., Sun, Y., Tang, Z., & Dong, Z. (2022a). Accelerating the decarbonization of carbonaceous gold ore by suspension oxidation roasting towards the improvement of gold leaching efficiency. Advanced Powder Technology, 33(11), 103833. https://doi.org/10.1016/j.apt.2022.103833

Xiao, H., Wei, S., Li, H., Zhao, L., Ma, S., & Luo, S. (2026). Fluidized roasting of carbonaceous gold ore in O_2/CO_2 atmosphere: Effects of temperature on gold leaching and mineralogical transformations. Minerals, 16(9), 908. https://doi.org/10.3390/min16090908

Xu, T., He, L., Zheng, Y., Zou, X., Badrkhani, V., & Schillinger, D. (2021a). Experimental and numerical investigations of microwave-induced damage and fracture formation in rock. Journal of Thermal Stresses, 44(4), 513–528. https://doi.org/10.1080/01495739.2020.1865857

Xu, T., Yuan, Y., Heap, M. J., Zhou, G.-L., Perera, M. S. A., & Ranjith, P. G. (2021b). Microwave-assisted damage and fracturing of hard rocks and its implications for

CC BY

Nexus Science Review
INTERNATIONAL JOURNAL OF INTERDISCIPLINARY RESEARCH

Received: 21/09/2026 - **Accepted:** 12/10/2026
Vol: 01.05
DOI: 10.66104/xp85fb62
Pages: 1-32

effective mineral resources recovery. Minerals Engineering, 160, 106663. https://doi.org/10.1016/j.mineng.2020.106663

Yang, J., Zhu, P., Li, H., Li, Z., Huo, X., & Ma, S. (2023). Research on the relationship between multi-component complex ore and its component minerals' grinding characteristics under abrasion force. Minerals, 13(1), 6. https://doi.org/10.3390/min13010006

Yuan, Y., Shao, Z., Qiao, R., Fei, X., & Wu, D. (2021). Quantifying damage evolution within olivine basalt based on crack propagation behavior under microwave irradiation. International Journal of Damage Mechanics, 30(10). https://doi.org/10.1177/10567895211017318

Zhang, D.-C., Xiao, Q.-K., Liu, W.-F., Chen, L., Yang, T.-Z., & Liu, Y.-N. (2016). Acid leaching decarbonization and following pressure oxidation of carbonic refractory gold ore. Journal of Central South University, 23(7), 1584–1590. https://doi.org/10.1007/s11771-016-3212-z

Zhang, L., Guo, X., Tian, Q., Zhong, S., & Qin, H. (2022a). Extraction of gold from typical Carlin gold concentrate by pressure oxidation pretreatment—Sodium jarosite decomposition and polysulfide leaching. Hydrometallurgy, 208, 105743. https://doi.org/10.1016/j.hydromet.2021.105743

Zhang, X., Zhu, Y., Sun, C., & Kou, J. (2022b). The mechanism of microwave-induced phase transformation and sulfur conversion in gold-bearing pyrite under inert atmospheres. Minerals Engineering, 186, 107742. https://doi.org/10.1016/j.mineng.2022.107742

Zhang, Y., Li, Q., Liu, X., Xu, B., Yang, Y., & Jiang, T. (2019). A thermodynamic analysis on the roasting of pyrite. Minerals, 9(4), 220. https://doi.org/10.3390/min9040220

Zhang, Y.-P., Yang, K., Fang, Y., Robledo-Cabrera, A., Peng, C.-S., & Lopez-Valdivieso, A. (2021). Roasting temperature effect on the recovery of refractory gold and silver in pyrite concentrates. Journal of Mining and Metallurgy, Section B: Metallurgy, 57(2), 235–243. https://doi.org/10.2298/JMMB200911019Z

Zhang, Z., Zhang, Q., Zou, G., & Chen, F. (2024). Effect of microwave irradiation on mechanical properties and microstructures of minerals. Minerals, 14(6), 623. https://doi.org/10.3390/min14060623

Zhu, F., Zhang, L., Li, H., Yin, S., Koppala, S., Yang, K., & Li, S. (2018). Gold extraction from cyanidation tailing using microwave chlorination roasting method. Metals, 8(12), 1025. https://doi.org/10.3390/met8121025

CC BY