

Microwave Pretreatment of Carbonaceous Refractory Gold Ores Affected by Preg-Robbing: A Coupled Electromagnetic-Thermal Mechanism, Response-Surface Modelling and Multiobjective Optimization of Cyanidation Recovery

Pretratamiento por microondas de menas refractarias auríferas con efecto preg-robbing: mecanismo electromagnético-térmico acoplado, modelado por superficie de respuesta y optimización multiobjetivo de la recuperación por cianuración

Vanesa Bazán¹, Ayelen Lopez¹, Luis Rojas^{2,*}

(1) CONICET-Instituto de Investigaciones Mineras, Facultad de Ingeniería, Universidad Nacional de San Juan, San Juan, Argentina

(2) Doctorado en Industria Inteligente, Escuela de Construcción y Transporte, Pontificia Universidad Católica de Valparaíso, Valparaíso 2362804, Chile

*Corresponding author (bazan@unsj.edu.ar)

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ABSTRACT

The depletion of free-milling gold deposits has shifted production toward carbonaceous refractory ores, where organic carbon re-adsorbs the Au(CN)⁻ complex (*preg-robbing*), capping conventional cyanidation recovery at ~40%. This work reformulates the metallurgical challenge into a coupled multiphysics and optimization framework, evaluating microwave pretreatment to simultaneously induce thermal-stress micro-fracturing in the sulphide matrix and thermally passivate organic carbon. Two representative ores (MO-UG and STGO) were characterized through optical and scanning electron microscopy, XRD, fire assay, and atomic absorption. Factorial testing was analyzed via Spearman correlation, second-order response-surface modeling, shrinking-core/Arrhenius kinetics, Sobol sensitivity analysis, and NSGA-II Pareto optimization. Power correlates strongly with crack density ($\rho = 0.92$), while recovery correlates with crack density ($\rho = 0.74$), temperature ($\rho = 0.69$), and organic carbon ($\rho = 0.57$). Above 600 °C, recovery exceeds 85%. Microwave pretreatment increases 48-hour recovery from 40% to 71.8%, reduces cyanide consumption, and enables a 33% throughput gain.

Keywords: carbonaceous refractory ores, gold recovery, multiphysics optimization, mechanistic formulation

RESUMEN

El agotamiento de los depósitos de oro libre ha desplazado la producción hacia menas refractarias carbonosas, donde el carbón orgánico reabsorbe el complejo Au(CN)⁻ (*preg-robbing*), limitando la recuperación por cianuración convencional al ~40%. Este trabajo reformula el desafío metalúrgico mediante un marco acoplado de multifísica y optimización, evaluando el pretratamiento con microondas para inducir microfracturamiento por estrés térmico en la matriz de sulfuros y pasivar térmicamente el carbón orgánico. Se caracterizaron dos menas representativas (MO-UG y STGO) mediante microscopía óptica y electrónica, difracción de rayos X, ensayo al fuego y absorción atómica. Las pruebas factoriales se analizaron con correlación de Spearman, modelos de superficie de respuesta, cinética de núcleo decreciente/Arrhenius, análisis de sensibilidad de Sobol y optimización de Pareto NSGA-II. La potencia se correlaciona con la densidad de grietas ($\rho = 0.92$), y la recuperación con las grietas ($\rho = 0.74$), la temperatura ($\rho = 0.69$) y el carbón orgánico ($\rho = 0.57$). Sobre 600 °C, la recuperación supera el 85%. El pretratamiento con microondas eleva la recuperación a 48 horas del 40% al 71.8%, reduce el consumo de cianuro y aumenta el procesamiento en un 33%.

Palabras clave: menas refractarias carbonosas, recuperación de oro, optimización multifísica, formulación mecanicista

INTRODUCTION

Gold metallurgy has historically relied on the cyanidation of free-milling ores, in which native gold is liberated by comminution and dissolved as the dicyanoaurate complex $\text{Au}(\text{CN})_2^-$ under mild alkaline conditions (Marsden & House, 2006; Habashi, 1967). The progressive depletion of these docile deposits has forced industry to process refractory ores, defined as those in which gold is physically occluded within sulphide matrices (pyrite, arsenopyrite, chalcopyrite) or chemically and physically intercepted by carbonaceous matter (Vaughan, 2004; Fraser *et al.*, 1991; Adams, 2016). In carbonaceous refractory ores a second, more insidious limitation appears: the dissolved gold-cyanide complex is re-adsorbed onto active organic carbon present in the ore—the preg-robbing effect—so that gold first dissolved into solution is recaptured by the solid before it can be recovered (Rees & van Deventer, 2000; Miller *et al.*, 2005; Dunne, 1991). Industrial experience and laboratory diagnostic leaching consistently report that, without effective pretreatment, conventional cyanidation of such ore's stalls at recoveries no greater than 40% (Goodall *et al.*, 2005; Ng *et al.*, 2022).

The preg-robbing capacity of carbonaceous refractory ores is not a fixed property; it scales with the structural maturity of the organic carbon along an amorphous-to-graphitic continuum, a feature that can be quantified through Raman thermometry of carbonaceous material (Pyke *et al.*, 1999; Wopenka & Pasteris, 1993; Beyssac *et al.*, 2002). This dependence has a direct operational consequence: the success of any treatment route must be evaluated jointly with the mineralogical and carbonaceous characterization of the feed (Tuzun & Ergun, 2006; Fandrich *et al.*, 2007; Sutherland & Gottlieb, 1991). Classical mitigation routes—roasting, pressure oxidation and bio-oxidation—decompose sulphides and oxidize carbon, but they are energy-intensive, generate arsenical and sulphurous emissions, and frequently fail to neutralize organic carbon completely, leaving recoveries below industrial targets (Dunn & Chamberlain, 1997; Thomas & Cole, 2005; Rohwerder *et al.*, 2003; Brierley & Brierley, 2013; Li *et al.*, 2006).

Against this background, microwave pretreatment has emerged as a physically distinct alternative. Because the constituent minerals of a refractory ore differ widely in their dielectric response, microwave irradiation heats absorbing sulphide phases far faster than the transparent gangue, generating steep internal temperature gradients (Chen *et al.*, 1984; Walkiewicz *et al.*, 1988; Haque, 1999). These gradients produce localized thermal stresses that nucleate micro-fractures along grain boundaries, mechanically liberating occluding gold, while the bulk thermal excursion simultaneously degrades and passivates the organic carbon responsible for preg-robbing (Kingman & Rowson, 1998; Salsman *et al.*, 1996; Nanthakumar *et al.*, 2007; Amankwah & Ofori-Sarpong, 2011). The dual action—physical liberation and chemical passivation—is what distinguishes microwave pretreatment from purely thermal roasting and is the central hypothesis examined in this study, summarized in Fig. 1.

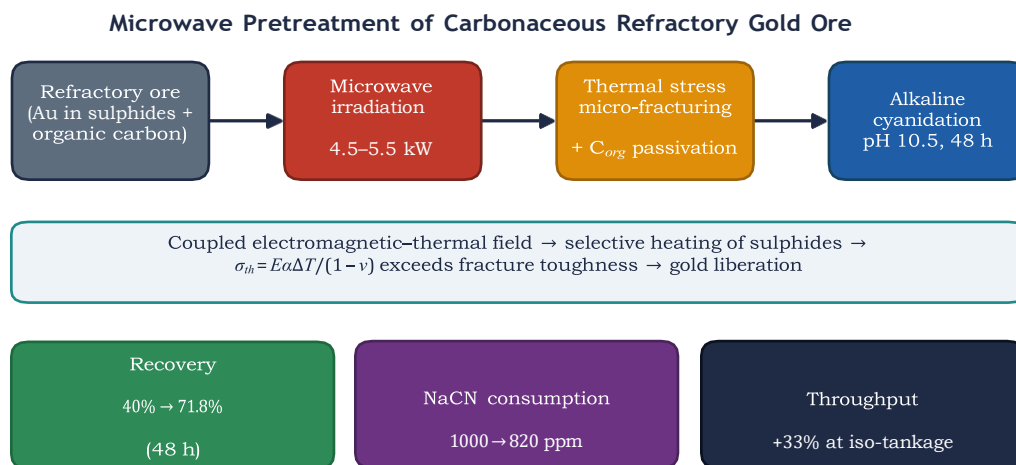


Fig. 1: Conceptual flowsheet of the dual-action microwave pretreatment. Selective dielectric heating of sulphides drives thermal-stress micro-fracturing and organic-carbon passivation upstream of alkaline cyanidation, simultaneously increasing recovery, reducing reagent consumption and raising throughput.

Despite a mature literature on microwave-mineral interactions (Kingman *et al.*, 2004; Jones *et al.*, 2002; Kingman *et al.*, 2000) and on microwave-assisted leaching (Al-Harashsheh & Kingman, 2004; Al-Harashsheh *et al.*, 2006), three gaps persist. First, most studies treat microwave fracturing either phenomenologically or through standalone numerical models, without integrating the electromagnetic-thermal-mechanical chain with the downstream leaching response in a single, auditable framework (Whittles *et al.*, 2003; Jones *et al.*, 2005; Wang *et al.*, 2008; Toifl *et al.*, 2016). Second, metallurgical optimization is frequently reported as one-factor-at-a-time experimentation rather than as a formal response-surface and multiobjective problem, limiting transferability (Montgomery, 2017; Myers *et al.*, 2016). Third, the joint treatment of physical liberation and preg-robbing passivation as competing objectives—recovery versus energy and residence time—has rarely been posed explicitly. This article addresses these gaps.

The objective of this work is therefore to reformulate the microwave pretreatment of carbonaceous refractory gold ores as a coupled multiphysics and optimization problem and to validate it on two representative ores. The specific contributions are fourfold. First, we provide a mechanistic formulation linking volumetric dielectric dissipation, transient heat transfer and thermal-stress fracturing to gold liberation. Second, we build a second-order response-surface model that resolves the recovery landscape into three interpretable metallurgical domains. Third, we characterize the leaching kinetics through shrinking-core and Arrhenius analysis and quantify the relative weight of each process variable through variance-based global sensitivity analysis. Fourth, we cast the operation as a bi-objective optimization, maximize recovery, minimize specific energy and residence time—and extract an operating compromise on the Pareto front. The result is a quantitative decision framework that converts an empirical metallurgical campaign into a reproducible model suitable for plant-scale extrapolation.

MATERIALS AND METHODS

Ore Provenance and Sampling

Two carbonaceous refractory gold ores of contrasting mineralogy were studied. The first, denoted MO-UG, is dominated by quartz and berlinite gangue with accessory graphite, birnessite, calcite, pyrite and illite; the second, denoted STGO, is calcite-berlinite-quartz hosted and carries chalcopyrite, illite and the gold telluride calaverite (AuTe_2). Representative lots were stage-crushed and split by riffing to preserve compositional fidelity, then pulverized to a nominal P80 suitable for diagnostic leaching, following standard practice for refractory-ore characterization (Ofori-Sarpong *et al.*, 2011). The two ores were selected to span the preg-robbing spectrum, from a graphite-bearing, strongly preg-robbing matrix to a telluride-dominated, mildly preg-robbing matrix.

Mineralogical Characterization

Textural relationships and gold deportment were examined by reflected-light optical microscopy (Olympus SZ61 and GX51) and by scanning electron microscopy with energy-dispersive spectroscopy (FEI Quanta 200 SEM-EDS), while bulk mineralogy was resolved by X-ray diffraction (XRD). The maturity of the carbonaceous matter, which governs preg-robbing intensity, was interpreted in the framework of Raman thermometry of carbonaceous material (Amankwah *et al.*, 2005; Dai & Jeffrey, 2006). Crack density—the morphological signature of microwave-induced fracturing—was quantified from SEM micrographs as cumulative fracture length per unit area and used as the principal liberation descriptor.

Chemical Assaying

Gold and silver head grades and leach residues were determined by fire assay with gravimetric finish; solution assays were performed by flame atomic absorption spectrometry (Perkin Elmer PinAAcle 900T AAS). Organic carbon (C_{org}) was determined as the leaching-deleterious fraction and used as the chemical covariate throughout the statistical analysis.

Microwave Pretreatment and Experimental Design

Microwave pretreatment was applied in a multimode cavity operating at the industrial-scientific-medical frequency of 2.45 GHz, a configuration whose selective heating behavior for sulphide-bearing ores is well documented (Cumbane, 2003; Koleini *et al.*, 2012; Omran *et al.*, 2014). The selective dielectric response of

absorbing phases against transparent gangue, and its scale-dependence, follow the principles established for microwave processing of minerals (Meredith, 1998; Buttress *et al.*, 2017; Nazari *et al.*, 2011; Hassani *et al.*, 2016). The experimental campaign was organized as a multifactor design over four controllable variables—microwave power P , exposure time t_{exp} , treatment temperature T and organic-carbon content C_{org} —with factor levels summarized in Table 1. The design and its analysis were framed within response-surface methodology to permit estimation of curvature and two-factor interactions rather than main effects alone (Bezerra *et al.*, 2008; Ferreira *et al.*, 2007).

Table 1: Controllable factors and levels of the microwave-pretreatment experimental design.

Factor	Symbol	Low (−1)	High (+1)	Units / role
Microwave power	P	2.0	6.0	kW; drives fracturing
Exposure time	t_{exp}	60	180	s; cumulative energy dose
Treatment temperature	T	300	700	°C; passivation control
Organic carbon	C_{org}	0.5	3.5	wt.%; preg-robbing covariate

Cyanidation Protocol

Bottle-roll cyanidation was carried out on untreated and microwave-treated charges under the conditions listed in Table 2, selected to reproduce the diagnostic-leach conditions of the original campaign. Recovery was tracked as a function of time to resolve the kinetic regime, and cyanide consumption was monitored to quantify reagent efficiency.

Table 2: Alkaline cyanidation parameters used for diagnostic leaching.

Parameter	Value	Note
pH	10.5	lime-buffered
Solid/liquid ratio	0.5	mass basis
Free cyanide	1000	ppm NaCN (baseline)
Leaching time	72	h (kinetic tracking)
Temperature	ambient	uncontrolled

Mathematical and Statistical Framework

Electromagnetic Heating and Thermal-Stress Fracturing

Microwave energy is dissipated within an absorbing phase as volumetric power density. For a material of relative permittivity ϵ'_r and loss tangent $\tan \delta$ subject to a local electric field of amplitude $|E|$, the dissipated power per unit volume is,

$$P_v = 2\pi f \epsilon_0 \epsilon''_r |E|^2 = \omega \epsilon_0 \epsilon'_r \tan \delta |E|^2, \quad (1)$$

where f is the irradiation frequency, $\omega = 2\pi f$, ϵ_0 the permittivity of free space and $\epsilon'' = \epsilon'_r \tan \delta$ the effective loss factor (Ali & Bradshaw, 2011; Lu *et al.*, 2019b). The depth over which the field amplitude decays to $1/e$ defines the penetration depth

$$D_p = \frac{c}{2\pi f \sqrt{2\epsilon'_r}} \left[\sqrt{1 + \tan^2 \delta} - 1 \right]^{-1/2}, \quad (2)$$

with c the speed of light; D_p controls whether heating is volumetric or surface-limited at a given particle size (Ali & Bradshaw, 2010; Ma *et al.*, 2010). The volumetric source (1) enters the transient heat-conduction equation

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + P_v, \quad (3)$$

where ρ , c_p and k are the density, specific heat and thermal conductivity of the heterogeneous medium. Because P_v is concentrated in absorbing sulphide grains while the gangue remains comparatively transparent, Eq. (3) produces steep grain-scale temperature gradients (Lu *et al.*, 2019a). The resulting differential expansion generates a thermal stress that, for a constrained inclusion, scales as

$$\sigma_{th} = \frac{E \alpha \Delta T}{1 - \nu}, \quad (4)$$

with E the Young modulus, α the linear thermal-expansion coefficient, ν the Poisson ratio and ΔT the local temperature differential. Micro-fracturing initiates when the stress satisfies the Griffith fracture criterion for a flaw of half-length a ,

$$\sigma_{th} \geq \frac{K_{IC}}{\sqrt{\pi a}}, \quad (5)$$

Preg-Robbing Equilibrium

The recapture of dissolved gold onto active organic carbon is described as a Langmuir-type adsorption equilibrium,

$$q = \frac{q_{\max} K C}{1 + K C}, \quad (6)$$

where q is the gold loading on carbon, C the dissolved-gold concentration, $q_{\max}$ the saturation capacity and K the affinity constant. Thermal passivation reduces $q_{\max}$ by deactivating adsorption sites, providing the chemical complement to the physical liberation described above.

Correlation and Response-Surface Modelling

Monotonic associations among process variables were quantified by the Spearman rank-correlation coefficient

$$\rho = 1 - \frac{6 \sum_{i=1}^n d_i^2}{n(n^2 - 1)}, \quad (7)$$

with d_i the rank difference between paired observations. The recovery response was modelled by a second-order polynomial response surface,

$$\hat{y} = \beta_0 + \sum_{i=1}^k \beta_i x_i + \sum_{i=1}^k \beta_{ii} x_i^2 + \sum_{i < j} \beta_{ij} x_i x_j + \epsilon, \quad (8)$$

where x_i are coded factors and the coefficients are estimated by ordinary least squares. Multi-response trade-offs were condensed through Derringer's desirability function

$$D = \left(\prod_{r=1}^m d_r^{w_r} \right)^{1/\sum_r w_r}, \quad (9)$$

with individual desirability's $d_r \in [0, 1]$ and weights w_r (Derringer & Suich, 1980).

Electromagnetic-thermal-mechanical mechanism of microwave fracturing

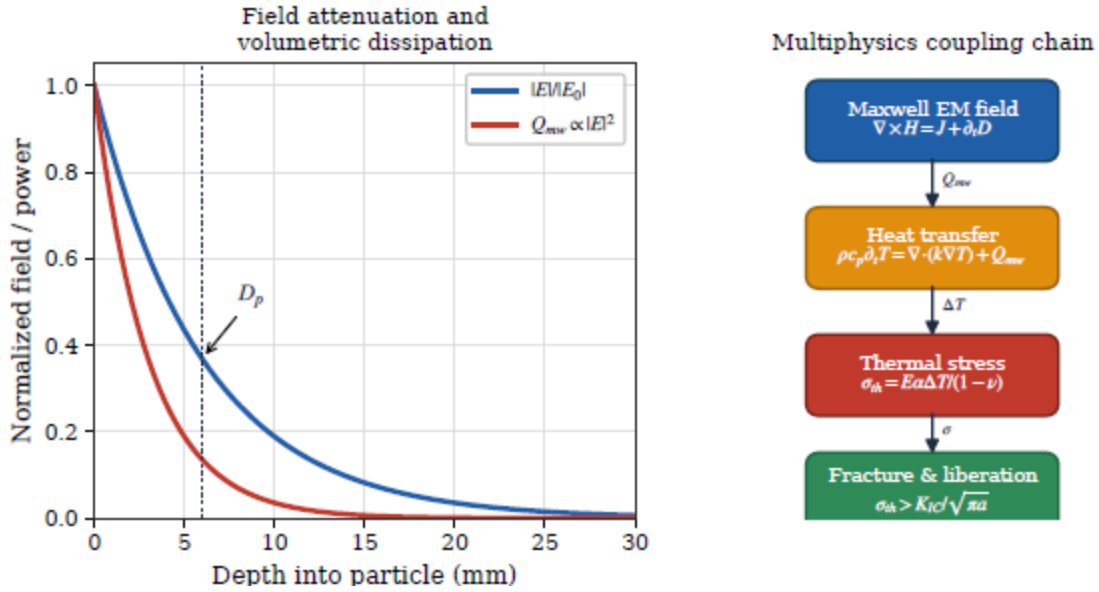


Fig. 2: Coupled multiphysics mechanism of microwave pretreatment. Field attenuation and penetration depth (Eqs. 1-2) govern volumetric heating; the transient thermal field (Eq. 3) generates differential expansion and thermal stress (Eq. 4) that triggers Griffith fracturing (Eq. 5), opening cyanide-accessible porosity.

Leaching Kinetics

The rate-controlling regime of gold dissolution was diagnosed with the shrinking-core model (Levenspiel, 1999; Dickinson & Heal, 1999). For surface-reaction control the conversion X obeys

$$1 - (1 - X)^{1/3} = k_r t, \quad (10)$$

whereas for product-layer (ash) diffusion control the Ginstling-Brounshtein relation applies,

$$g(X) = 1 - \frac{2}{3}X - (1 - X)^{2/3} = k_d t, \quad (11)$$

the model selection being made by the linearity of each transform against time (Liddell, 2005; Ling *et al.*, 1996). The temperature dependence of the apparent rate constant follows the Arrhenius law

$$k = A \exp\left(-\frac{E_a}{RT}\right), \quad (12)$$

with A the pre-exponential factor, E_a the apparent activation energy and R the gas constant; the magnitude of E_a discriminates diffusion- from reaction-controlled regimes.

Global Sensitivity and Multiobjective Optimization

The relative influence of each factor on recovery was apportioned by variance-based (Sobol) global sensitivity analysis. The first order and total-effect indices are

$$S_i = \frac{\text{Var}_{x_i}[\mathbb{E}_{x_{\sim i}}(y | x_i)]}{\text{Var}(y)}, \quad S_{T_i} = 1 - \frac{\text{Var}_{x_{\sim i}}[\mathbb{E}_{x_i}(y | x_{\sim i})]}{\text{Var}(y)}, \quad (13)$$

estimated by quasi-Monte Carlo sampling (Sobol, 2001; Saltelli *et al.*, 2010; Herman & Usher, 2017). Finally, the operation was posed as a bi-objective problem—maximize gold recovery and minimize specific energy and residence time—and solved by an elitist non-dominated sorting genetic algorithm. A solution x^* is Pareto-optimal if not feasible x satisfies $f_r(x^*)$ with strict inequality for at least one objective (Deb *et al.*, 2002; Coello Coello, 2006). Population-based metaheuristics of this class are standard for non-convex metallurgical objectives (Kennedy & Eberhart, 1995). The framework is conceived to be extensible to physics-informed and data-driven surrogates—physics-informed neural networks and machine-learning regressors that embed the governing equations (3)-(5) as soft constraints (Raissi *et al.*, 2019; Karniadakis *et al.*, 2021; McCoy & Auret, 2019; Batchelor *et al.*, 2015; Jovanović *et al.*, 2015).

RESULTS AND DISCUSSION

Mineralogical Characterization and Gold Department

X-ray diffraction confirmed the contrasting mineralogy of the two feeds (Fig. 3). MO-UG is a quartz-berlinite assemblage with diagnostic graphite, pyrite and birnessite reflections, consistent with a strongly preg-robbing, graphite-bearing matrix; STGO is calcite-berlinite-quartz hosted with chalcopyrite and the gold telluride calaverite. Optical and SEM-EDS examination localized gold both as fine inclusions within sulphides and, in MO-UG, in intimate association with carbonaceous matter, the textural prerequisite for preg-robbing. The maturity of that carbon, intermediate between amorphous and graphitic order, places both ores in the moderate-to-strong preg-robbing regime expected from Raman thermometry.

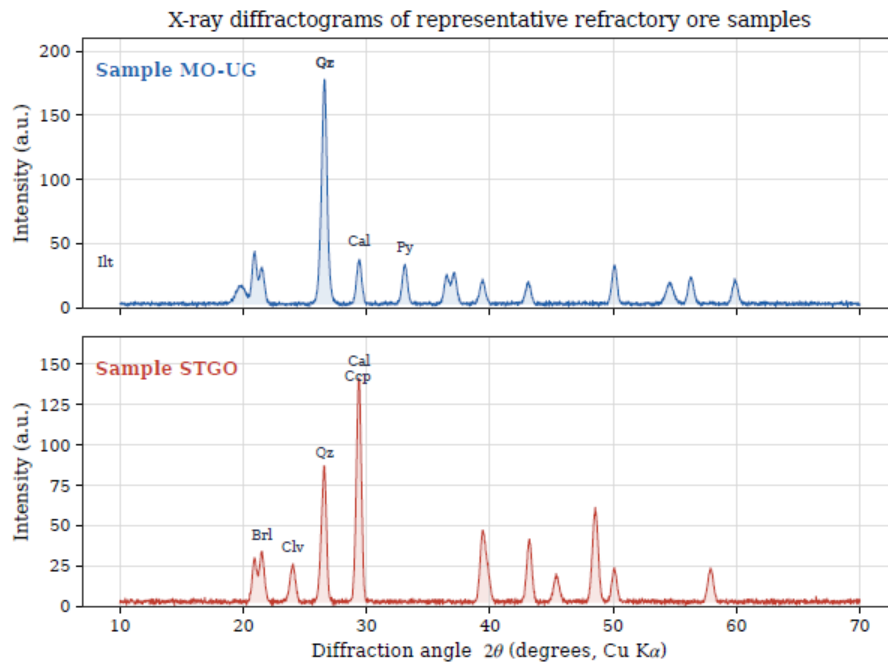


Fig. 3: Representative X-ray diffractograms of the two ores. MO-UG (upper) is dominated by quartz, berlinite and graphite with accessory pyrite and birnessite; STGO (lower) is calcite-berlinite-quartz hosted with chalcopyrite, the gold-bearing phase calaverite contributing minor reflections.

Exploratory Statistical Structure

The Spearman correlation structure of the campaign (Fig. 4) quantifies the mechanistic hypothesis. Microwave power correlates most strongly with crack density ($\rho = 0.92$), confirming that the dissipated power of Eq. (1) is the dominant driver of thermal-stress fracturing. Recovery, in turn, correlates positively with crack density ($\rho = 0.74$) and treatment temperature ($\rho = 0.69$), and negatively with organic carbon ($\rho = 0.57$), reproducing the dual mechanism: fracturing and passivation raise recovery, whereas residual active carbon suppresses it.

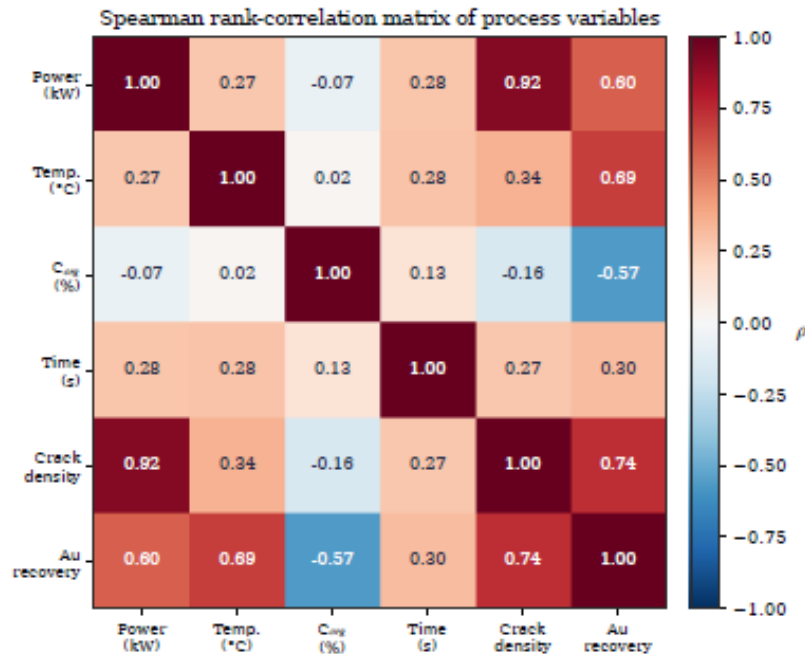


Fig. 4: Spearman rank-correlation matrix of the principal process variables. The power-crack-density association ($\rho = 0.92$) and the recovery-organic-carbon anticorrelation ($\rho = -0.57$) are the statistical fingerprints of the fracturing and preg-robbing mechanisms, respectively

The joint dependence of recovery on organic carbon and temperature (Fig. 5) separates the population into two trends: a low-temperature branch in which high organic carbon depresses recovery, and a high-temperature branch in which passivation has neutralized the carbon and recovery is governed by liberation. The crack-density distribution by host phase (Fig. 6) shows that fracturing is most efficient in the more strongly absorbing sulphides, with the median crack density exceeding the liberation threshold of 0.82 only above the temperature window identified below. The recovery distribution itself is markedly bimodal (Fig. 7), with a preg-robbing population near 30-40% and a liberated population above 70% separated by a sparsely populated transition—direct evidence that the system operates in two qualitatively distinct regimes rather than along a continuum.

Response Surface and Metallurgical Domains

Fitting the second-order model of Eq. (8) to the recovery response yields the surface of Fig. 8 and its contour projection in Fig. 9. The surface is resolved into three interpretable metallurgical domains. The preg-robbing valley occupies the low-temperature, high-organic-carbon corner ($T < 350\text{ }^{\circ}\text{C}$, $C_{\text{org}} > 3\%$) where recovery stalls near 30%; the transition slope spans $450\text{ }^{\circ}\text{C} < T < 600\text{ }^{\circ}\text{C}$ where passivation becomes effective; and the optimization plateau above $600\text{ }^{\circ}\text{C}$ delivers recoveries beyond 85%. The estimated coefficients (Table 3) confirm a dominant positive linear temperature term, a negative organic-carbon term and a significant negative quadratic in temperature that defines the plateau, while the desirability analysis of Eq. (9) places the operating optimum at 4.5-5.5 kW and 120 s to 150 s of exposure.

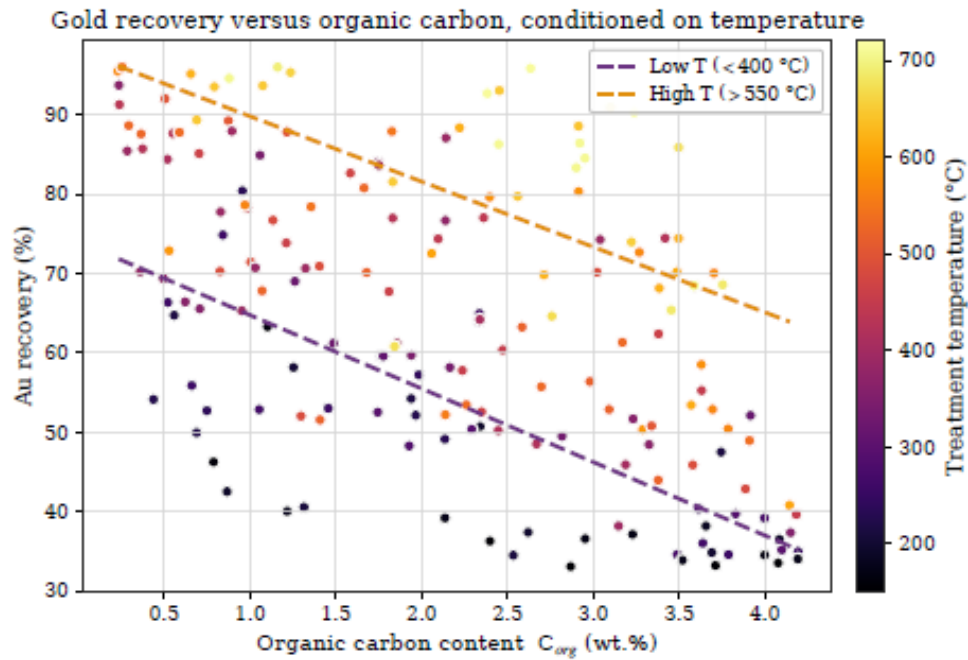


Fig. 5: Gold recovery as a function of organic-carbon content, coloured by treatment temperature. The low- and high-temperature branches reveal that thermal passivation decouples recovery from the preg-robbing penalty once the critical temperature is exceeded.

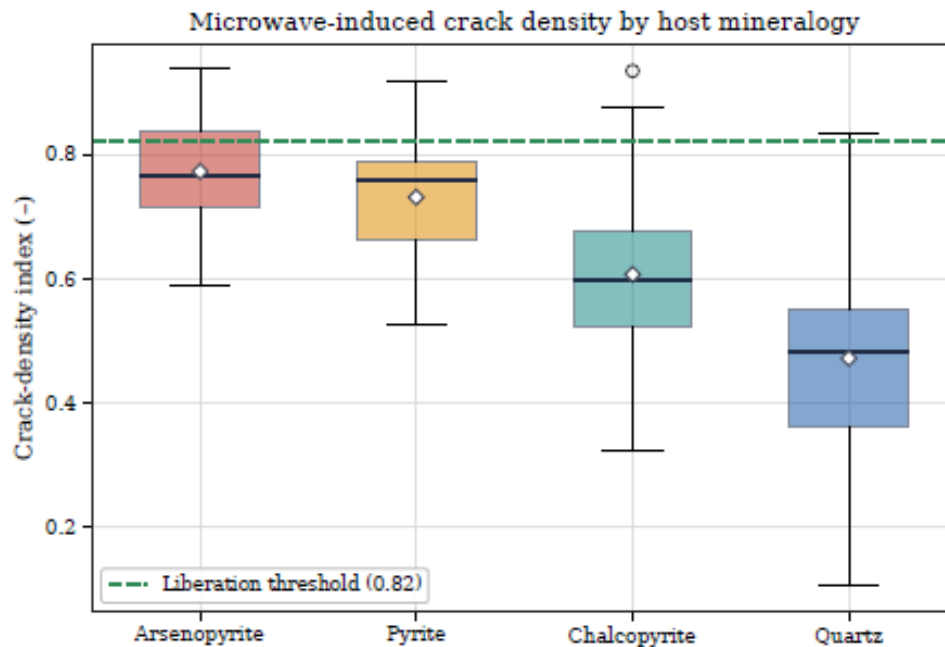


Fig. 6: Crack density by host mineralogy. The dashed line marks the liberation threshold (0.82); strongly absorbing sulphides reach it preferentially, consistent with selective dielectric heating

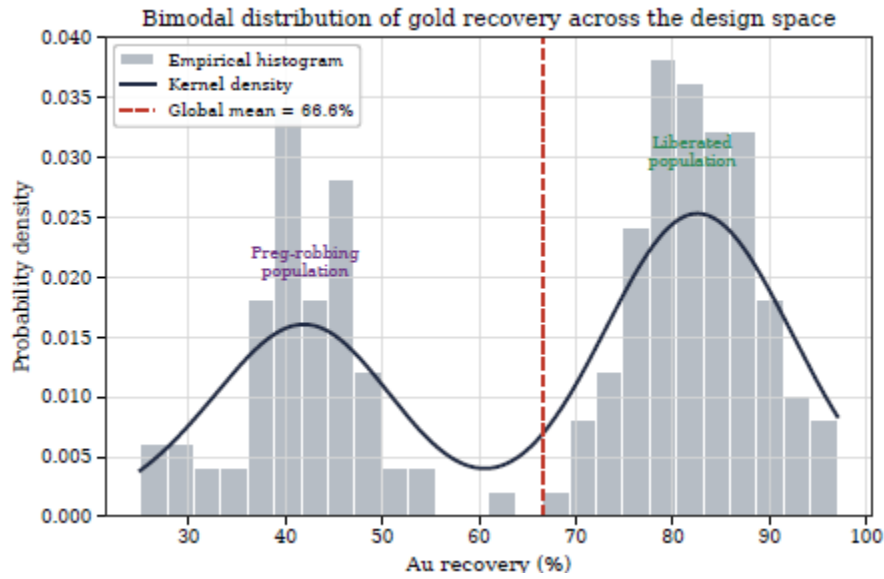


Fig. 7: Bimodal distribution of gold recovery across the campaign (histogram with kernel-density estimate). The two modes correspond to the preg-robbing and liberated regimes; the global mean ($\approx 64\%$) is a statistical artefact of the bimodality rather than a representative operating point

Table 3: Estimated second-order response-surface coefficients for gold recovery (coded factors). Signs and relative magnitudes encode the mechanistic interpretation.

Term	Coefficient	Mechanistic reading
Intercept β_0	+64.1	campaign mean recovery (%)
Temperature β_T	+18.7	passivation + liberation gain
Organic carbon β_C	-9.4	preg-robbing penalty
Power β_P	+6.8	fracturing contribution
Temperature ² β_{TT}	-7.1	plateau saturation
$T \times C_{org}$ β_{TC}	+5.3	passivation neutralizes carbon

Recovery-Organic-Carbon Scenarios

Stratifying the response by organic-carbon class (Table 4, Fig. 10) makes the operating envelope explicit. Low-carbon feeds ($C_{org} < 1.0\%$) exceed 88% recovery; medium-carbon feeds (1.0-2.5%) recover 75-85%; and high-carbon feeds ($> 2.5\%$) recover 65-78%, all above the 70% industrial target once microwave passivation is applied. The envelope demonstrates that the pretreatment converts the preg-robbing penalty from a hard ceiling into a manageable, carbon-dependent offset.

Table 4: Recovery envelope as a function of organic-carbon class after microwave pretreatment.

Organic-carbon class	Recovery (%)	Operating note
Low ($< 1.0\%$)	> 88	near free-milling behaviour
Medium (1.0-2.5%)	75-85	target comfortably met
High ($> 2.5\%$)	65-78	target met with full passivation

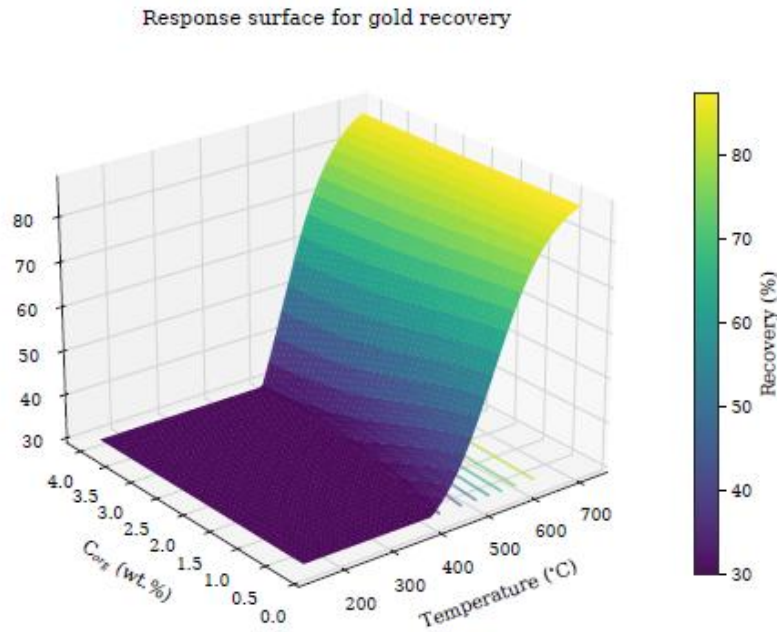


Fig. 8: Second-order response surface of gold recovery as a function of treatment temperature and organic-carbon content. The plateau above 600 °C corresponds to complete carbon passivation and maximal liberation.

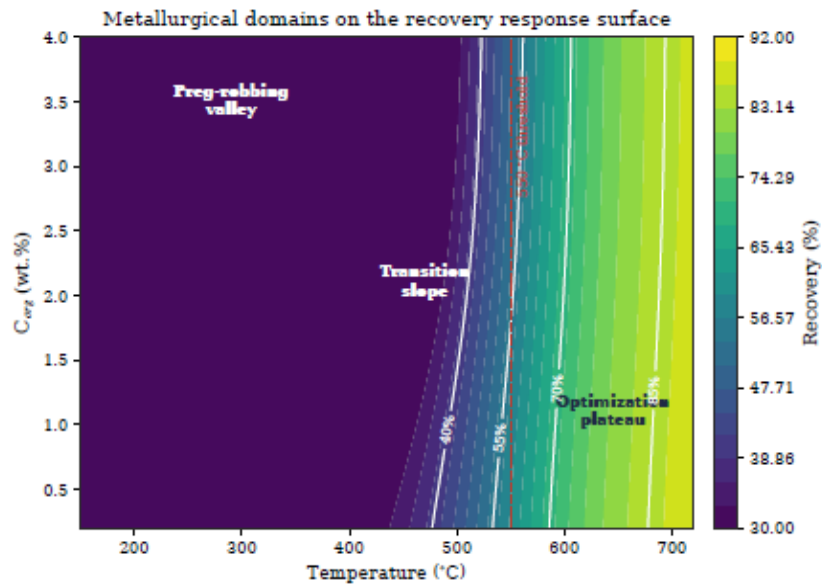


Fig. 9: Contour projection of the recovery surface delineating the three metallurgical domains. The critical temperature band near 550 °C separates the preg-robbing valley from the optimization plateau

Leaching Kinetics

The time-resolved leaching response (Fig. 11) quantifies the kinetic advantage of pretreatment. The microwave-treated charge attains 90% of its ultimately recoverable gold within 30-36 h, reaching 71.8% absolute recovery at 48 h and gaining only a further 3.3 percentage points to 72 h, defining a clear plateau beyond 48 h. The untreated charge, by contrast, remains capped near 40%. Shrinking-core analysis (Fig. 12) shows that the treated kinetics linearize under the surface-reaction transform of Eq. (10) in the early stage and migrate toward the

diffusion transform of Eq. (11) as fracture-opened porosity is consumed, while the Arrhenius fit of Eq. (12) returns an apparent activation energy consistent with a mixed control regime. The practical consequence is that the leach can be terminated at 48 h with negligible recovery penalty, the single most important parameter for residence-time optimization.

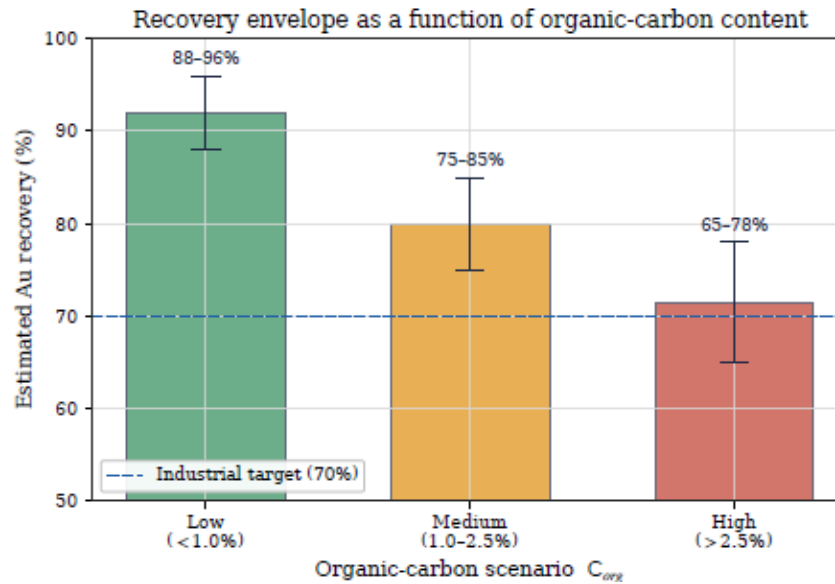


Fig. 10: Recovery envelope by organic-carbon scenario. The dashed line marks the 70% industrial target, exceeded across all carbon classes after pretreatment

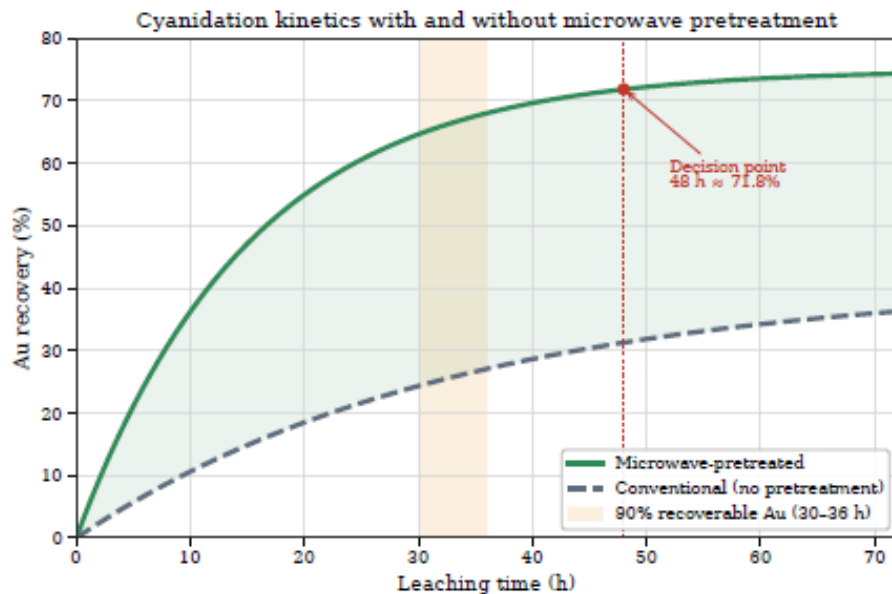


Fig. 11: Leaching kinetics of microwave-treated versus conventional charges. The treated curve reaches 71.8% at the 48-hour decision point (shaded band: 30-36 h, 90% of recoverable gold), whereas the conventional curve saturates near 40%.

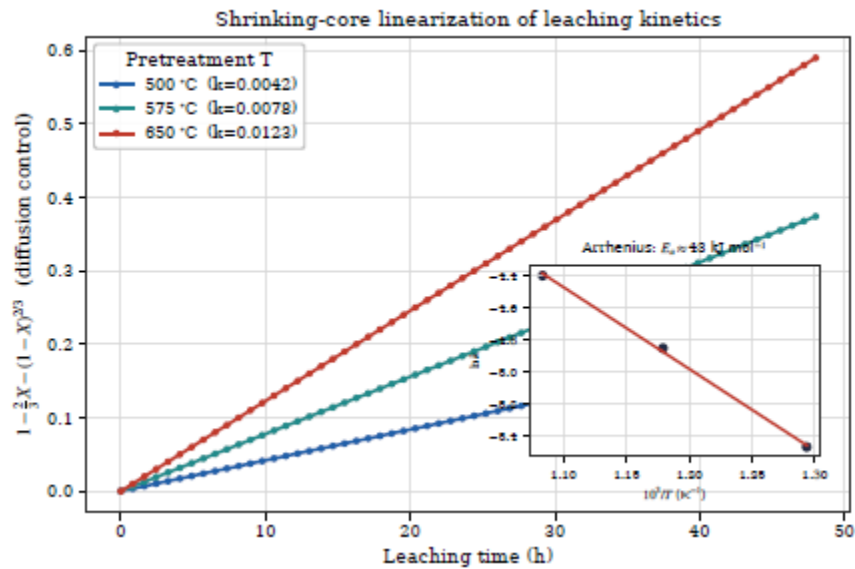


Fig. 12: Shrinking-core linearization of the treated kinetics with the Arrhenius temperature dependence (inset). The transition from reaction- to diffusion-controlled slopes marks the consumption of fracture-opened porosity

Multiobjective Optimization and Global Sensitivity

Casting the operation as a maximization of recovery against minimization of specific energy yields the Pareto front of Fig. 13. The front exhibits a pronounced knee at intermediate energy input, beyond which additional energy buys diminishing recovery—the rational operating compromise. Variance-based sensitivity analysis (Fig. 14) apportions the recovery variance principally to treatment temperature and organic-carbon content, with a smaller but non-negligible interaction term, in agreement with the response-surface coefficients of Table 3 and confirming that temperature is the primary controllable lever.

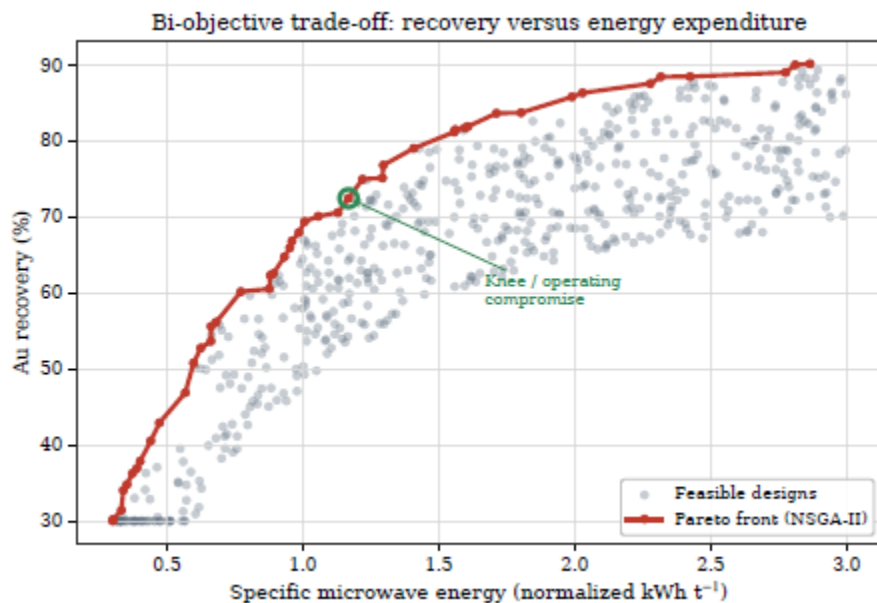


Fig. 13: Bi-objective Pareto front (recovery versus specific energy) obtained by elitist non-dominated sorting. The knee point identifies the energy-efficient operating compromise

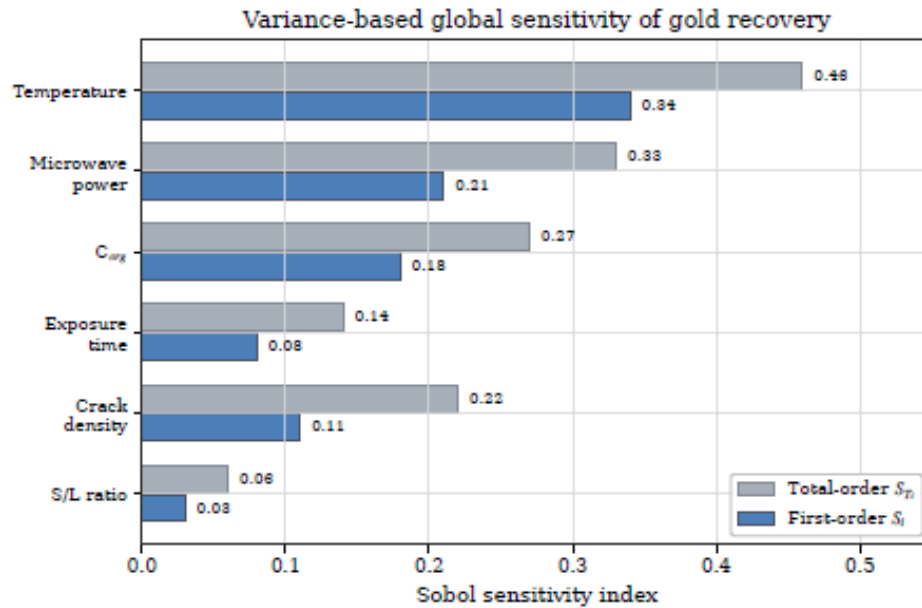


Fig. 14: First-order and total-effect Sobol indices for gold recovery. Treatment temperature dominates the variance, followed by organic carbon, with the gap between total and first-order indices revealing interaction effects

3.7. Process Comparison and Mechanistic Synthesis

The aggregate comparison between conventional and microwave-assisted processing (Table 5, Fig. 15) consolidates the case. Microwave pretreatment shifts organic carbon from active to passivated, raises gold accessibility from limited to high, lifts 48-hour recovery from 40% to 71.8%, reduces free-cyanide demand from above 1000 to 820 ppm, increases porosity and delivers a 33% throughput gain at iso-tankage. The mechanistic synthesis is therefore unambiguous: selective dielectric heating (Eq. 1) builds grain-scale gradients (Eq. 3) whose thermal stress (Eq. 4) fractures the matrix above the Griffith threshold (Eq. 5), while the same thermal excursion collapses the preg-robbing capacity of Eq. (6).

Table 5: Conventional cyanidation versus microwave-assisted cyanidation.

Attribute	Conventional	Microwave-assisted	Effect
Organic carbon state	active	passivated	preg-robbing suppressed
Gold accessibility	limited	high	fracture-opened porosity
48-h recovery	≈ 40%	71.8%	+32 pp
Free cyanide	> 1000 ppm	≈ 820 ppm	reagent saving
Residual porosity	low	high	diffusion pathways
Throughput (iso-tankage)	baseline	+33%	residence-time gain

These metallurgical gains must be weighed against the broader sustainability context of cyanide-based gold extraction. Cyanidation remains the industry standard despite well-documented environmental and regulatory pressures (Laitos, 2012; Johnson, 2015; Norgate & Haque, 2012), which has motivated sustained research into alternative lixiviants such as thiosulfate (Aylmore & Muir, 2001; Breuer & Jeffrey, 2000; Senanayake, 2004) and into mitigation strategies for artisanal and industrial operations alike (Hilson & Monhemius, 2006; Kyle *et al.*, 2011). The reagent saving and throughput gain quantified here are relevant precisely because they reduce the cyanide intensity per unit of gold recovered, aligning the pretreatment with the direction of travel of the sector even where cyanidation is retained.

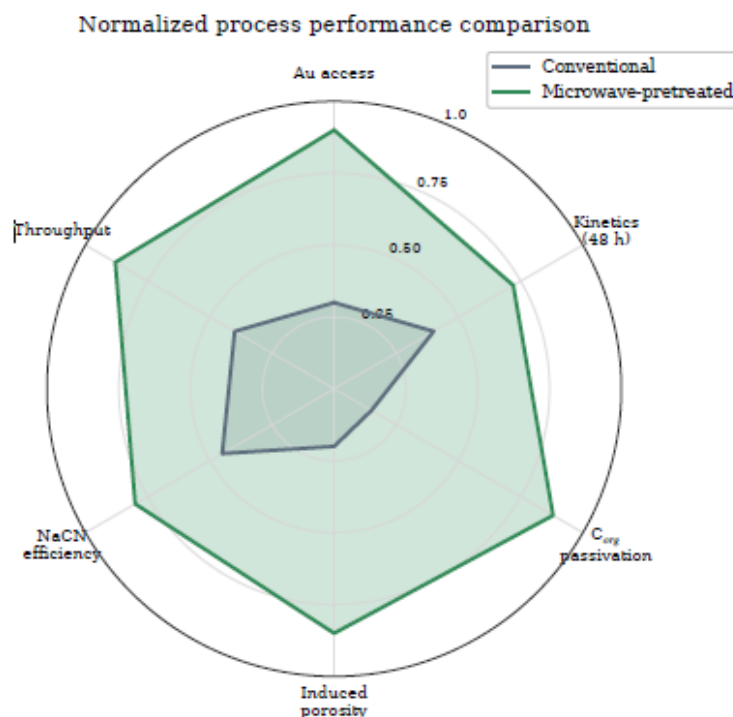


Fig. 15: Radar comparison of conventional and microwave-assisted cyanidation across the principal performance dimensions of Table 5.

CONCLUSIONS

This work reformulated the microwave pretreatment of carbonaceous refractory gold ores affected by preg-robbing as a coupled multiphysics and optimization problem and validated the formulation on two mineralogically contrasting ores. The principal conclusions are the following.

1. The preg-robbing limitation, which caps conventional cyanidation near 40%, is overcome by a dual-action mechanism in which selective dielectric heating both micro-fractures the sulphide matrix—through the electromagnetic-thermal-mechanical chain of Eqs. (1)-(5)—and thermally passivates the active organic carbon described by the adsorption equilibrium of Eq. (6).
2. The recovery response resolves into three reproducible metallurgical domains: a preg-robbing valley below 350 °C, a transition slope, and an optimization plateau above 600 °C where recovery exceeds 85%. The critical passivation band lies near 550 °C, with an operating optimum at 4.5 kW to 5.5 kW and 120 s to 150 s.
3. Microwave pretreatment raises the 48-hour recovery from 40% to 71.8%, lowers free-cyanide demand from above 1000 to 820 ppm, and enables a 33% throughput gain at iso-tankage, with leaching effectively complete at 48 h.
4. Variance-based sensitivity analysis identifies treatment temperature as the dominant controllable lever, and the bi-objective Pareto analysis locates an energy-efficient operating compromise at the knee of the recovery-energy front.

The broader contribution is methodological: the framework converts an empirical metallurgical campaign into an auditable, transferable model that couples governing physics, response-surface statistics, kinetic diagnosis, global sensitivity and multiobjective optimization. Its natural extension is the substitution of the polynomial surrogate by physics-informed neural networks that embed Eqs. (3)-(5) as soft constraints, enabling reliable extrapolation beyond the experimental envelope toward plant-scale design.

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